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Equity and modeling in sustainability science: Examples and opportunities throughout the process

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Equity is core to sustainability, but current interventions to enhance sustainability often fall short in adequately addressing this linkage. Models are important tools for informing action, and their development and use present opportunities to center equity in process and outcomes. This Perspective highlights progress in integrating equity into systems modeling in sustainability science, as well as key challenges, tensions, and future directions. We present a conceptual framework for equity in systems modeling, focused on its distributional, procedural, and recognitional dimensions. We discuss examples of how modelers engage with these different dimensions throughout the modeling process and from across a range of modeling approaches and topics, including water resources, energy systems, air quality, and conservation. Synthesizing across these examples, we identify significant advances in enhancing procedural and recognitional equity by reframing models as tools to explore pluralism in worldviews and knowledge systems; enabling models to better represent distributional inequity through new computational techniques and data sources; investigating the dynamics that can drive inequities by linking different modeling approaches; and developing more nuanced metrics for assessing equity outcomes. We also identify important future directions, such as an increased focus on using models to identify pathways to transform underlying conditions that lead to inequities and move toward desired futures. By looking at examples across the diverse fields within sustainability science, we argue that there are valuable opportunities for mutual learning on how to use models more effectively as tools to support sustainable and equitable futures.

equity | inequality | modeling | nature-society systems

Equitably enhancing human well-being is central to the goal of sustainability (1). Early discussions around sustainable development* highlighted that the goal of "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" (2) cannot be achieved without a focus on equity. It requires both the meaningful participation of all social groups and addressing disparities in the distribution of well-being—both between (inter) and within (intra) generations (3)—and their root causes. Building on this foundation, definitions of equity in sustainable development have increasingly attended to multiple and intersecting dimensions of social stratification (4), as well as relationality between humans and nature (5), across multiple sites and scales (6). In short, sustainable development aspires to "leave no one behind" (7).

To what extent have models of nature-society systems used to inform sustainable development supported the aim of equity, and what opportunities exist for improvement? Computational models are a core tool for exploring collective understanding of, and assessing interventions for, complex nature–society systems (8, 9). Models of these dynamic systems—often, though not exclusively, mechanistic models—are frequently used to consolidate knowledge about a system into a single representation which is then used to predict system

*Here, we acknowledge the fraught histories (150), critiques, tensions, and also constructive potential of the term "sustainable development" discussed in more detail in Liverman (151) and Sultana (152).

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behavior (10). They are also commonly used in a more exploratory fashion to ask "what-if" questions under various sets of assumptions (11) and articulate and clarify plural worldviews and perspectives (12, 13). Here, models are not framed narrowly as calculators generating outputs for decision support, but also as sites for decision framing and deliberation about multiple values, means, and ends (14). Both consolidative and exploratory modeling have been used to inform decision-making in a wide range of systems relevant to sustainable development (e.g., refs. 9, 11, 15, and 16). Models and their use therefore have the potential to help document, uncover drivers of, and transform inequities in nature-society systems.

Yet, many have argued that models and modeling practices in sustainability science have often omitted, simplified, or narrowly framed representations of human dimensions, and these limitations have precluded exploration of questions about inequity, agency, and power (17–20). Further, uncritical application of models or model-based metrics where equity is not explicitly considered has led to decisions that exacerbated existing disparities (see examples in ref. 21). Models are not only used to represent social processes and institutions (e.g., markets) but are also created and used within particular social and historical contexts, and so, their design may reflect or deepen existing inequities (17, 22, 23). Limited attention to who participates in modeling processes has also historically led to a focus on questions of interest for a narrow set of actors—often those with political, economic, and epistemic power (19, 22).

These practices may be shifting. Computational advances and increased data availability reduce the need to focus only on aggregates or single representative agents, which can obfuscate heterogenous preferences and outcomes (11, 24). There is now increased awareness in mainstream modeling communities about the importance of equity, in part due to the enhanced participation of a broader range of actors and disciplines that center questions of justice (19, 21, 25). These changes offer more possibilities for models to explore questions about equity in sustainable development; however, there is still much work to be done.

In this Perspective, our goal is to highlight promising examples of efforts to integrate equity into modeling for sustainable development, as well as key challenges, tensions, and future directions. We build on recent work that has asked this question in the context of specific sustainability-relevant systems (e.g., water, energy, climate) (11, 21, 26) or modeling methods (e.g., agent-based modeling, integrated assessment modeling, systems dynamics) (11, 27–29) to try to identify cross-cutting insights and promote learning between communities. We have included a positionality statement in *SI Appendix*, section S7 that shares and acknowledges the background and experiences that inform the examples we have chosen and our perspectives as an author team.

Conceptual Framework

Equity and justice are core to sustainability. The literature on these concepts is large, with many debates on definitions and metrics, and we acknowledge that the definitions below (and summarized in *SI Appendix*, Fig. S1) represent only one perspective. We distinguish between equality—a descriptive, relational concept about equal distribution (30)—and equity—a normative concept of what is considered "fair treatment or due reward" (31). Only a subset of inequalities may therefore be judged to be inequitable, and some inequalities may be needed to achieve equity (e.g., different needs for access). Because equity is normative and context-dependent, a single definition is elusive: as Harper et al. write, "judgments concerning inequity rely on social, political, and ethical discourse about what a society believes is unfair" (30). We use a definition of equity from Friedman et al. (with our adaptations in square brackets) (32): "a multi-dimensional concept of ethical concerns [and fairness] based on the distribution of costs and benefits, process and participation, and recognition, underpinned by the context under consideration." Following Romero-Lankao and Nobler, we define justice as systems, structures, and processes that "remov[e] barriers that prevent equity" and that equitably enhance well-being (33). As modeling reveals outcomes, in this perspective we focus on equity as an outcome of justice.

Equity is commonly analyzed through three dimensions (32, 34): distributive equity based on the distribution of "costs, responsibilities, rights versus benefits" (32); procedural equity, which focuses on decision-making processes (35), especially "the ability for stakeholders to meaningfully participate in decisions that affect them" (11); and recognitional equity based on "acknowledgment of and respect for distinct identities, histories, values, interests, and knowledge systems" (32) and "the idea that how we characterize people shapes our ability to consider their interests" (11). These three dimensions are not mutually exclusive but are often linked and reinforcing. Models are frequently used as tools to assess questions about distributional equity. Procedural and recognitional equity are linked to how and by whom models are developed and used and how modelers represent the conditions and values of different actors in models (11).

The interconnected nature of all three dimensions of equity is apparent in how distributive equity is operationalized in modeling processes, which requires specification of unit (what is being distributed), scope (to whom), and shape (which distributions are preferred or considered unfair) (36, 37). The answers to all three questions depend on who is influencing modeling decisions and therefore require attention to procedural and recognitional dimensions. Indeed, by whom is a matter of both the modelers and the knowledge and processes (e.g., co-production with stakeholders and rightsholders) that inform their choices.

In nature–society systems, the whats of interest might be benefits (e.g., timber) or burdens (e.g., air pollution exposure). Some of these benefits or burdens may be easily transferrable and thus could be redistributed to rectify inequities (e.g., income) and others not (e.g., access to biocultural heritage) (30). To whom is a question that is highly context dependent. In many contexts, the inequalities that exacerbate existing vulnerability and that arise from and further contribute to systematic marginalization of certain groups, are considered unfair (38). The social groups of interest for equity assessments may therefore vary based on place, time, and issue. In the United States, the environmental justice movement emerged from the organizing of Black, Indigenous, other People of Color, low-income, and migrant communities in response to disproportionate exposure to environmental burdens and lack of meaningful participation in decision-making (39, 40). In India, caste is highly relevant (41). The issue of scope is also strongly linked to recognitional equity. For instance, LGBTQ+ (lesbian, gay, bisexual, transgender, queer plus) communities have advocated for increased attention to how extreme weather and climate events can exacerbate risks for sexual and gender minorities (42). Critically, care must be taken to not identify and label groups as vulnerable without also addressing the historical and ongoing structures and systems that produce vulnerability (43).

The preferred shape of distributions is an important place where context-specific, normative judgments (i.e., preferred by whom and why) underlie quantitative equity analysis. Modelers have often adopted an implicitly utilitarian point of view, operationalized as the maximization of some aggregate, population-level utility function. For instance, in global (single-region) integrated assessment models such as DICE (Dynamic, Integrated Climate and Economics model), economic utility is maximized at the global scale and across time (44). Yet, when considering distribution, several preferred shapes are possible. Rawls-based notions of fairness focus on improving the conditions of the worst-off (45). This principle might be operationalized in an intergenerational context such as climate change by maximizing minimum utility across all future generations (46, 47). (In *SI Appendix*, section S1, we illustrate how the choice of metric embeds normative judgements about what is fair by calculating several example metrics for a single distribution.) Naive application of some metrics may also work against sustainability goals (e.g., an intervention that reduces inequality by reducing benefits to the best-off, without increasing, in an absolute sense, benefits to the worst-off) (21). Key complexities also include the nature of groups being compared (e.g., ordinal groups such as income vs. nominal groups such as ethnic/racialized minorities), whether distribution is considered both between and within groups (30), and consideration of the intersection of multiple social identities (4).

In the context of sustainability science, it is also critical to consider how distributional, procedural, and recognitional equity are enacted across generations (48). When the scope includes future generations who may not be able to represent their interests directly in the present, discussions about both distribution (e.g., what is a fair allocation of costs and benefits through time) and how procedural and recognitional equity can be enacted are challenging. For instance, these issues emerge in quantitative modeling of water allocations: In many jurisdictions, water rights embed preferred shapes in prioritizing the earliest (most senior) users in the basin (49). The use of social discount rates in many dynamic models, which embed assumptions about the weight of future costs and benefits in present-day terms, is another example (36, 50). However, modeling the dynamics of inequality and inequity over time (e.g., reinforcing or attenuating dynamics) is critical for informing equitable transitions, transformations, and adaptation pathways (11). Increasing concern about maladaptation to climate impacts (e.g., sea-level rise), where adaptive actions shift vulnerabilities to marginalized groups (48, 51), illustrate this need.

In sum, models of nature–society systems can illuminate questions of distribution, and their processes of development, use, and interpretation can also support procedural and recognitional equity. It is not the role of modelers alone to decide what is just or fair—these are broader, societal deliberations—but models can be used to explore the implications of adopting different conceptions of fairness such as the following: Would a given intervention exacerbate or reduce inequity, as defined a certain way? What are synergies and trade-offs across different equity dimensions? Further, modeling communities also have a responsibility to surface the underlying value assumptions and worldviews that are already built into current modeling practices and to create space for dialog about who and what is missing, and why.

Examples Throughout the Modeling Process

Below, we give examples from throughout the modeling process of meaningful engagement (or lack thereof) with all three dimensions of equity. Although the modeling process has been represented in many ways, we adapt the four stages described in Selin et al. (8) for modeling of dynamic systems as a framework for our discussion: identifying participants and defining model purpose; selecting modeled components; analyzing interactions; and assessing interventions. We draw examples from topical case studies of nature–society subsystems (i.e., water, energy, air quality, conservation), which are introduced in full in *SI Appendix*, section S2 and summarized in Fig. 1.

Identifying Participants and Defining Model Purpose. What is the purpose of modeling, and how does it fit within a larger analytic-deliberative process about sustainability (52)? Who gets to define this purpose, and participate in the modeling? Addressing these questions is the first stage of the modeling process, and decisions at this stage have important implications for subsequent steps of model development and application (53). If assessing distributional concerns (i.e., inequality or inequity) is not prioritized, model formulations may focus on aggregate representations and lack the granularity to speak to heterogeneity within and between populations. Historically, failure to attend to procedural and recognitional equity at this stage has also resulted in systematic marginalization of worldviews, limiting the kinds of data sources and decision options that are valued and represented and ultimately hindering sustainability goals (54).

Recent model applications illustrate opportunities to reframe the role of quantitative models in decision-making to enhance procedural and recognitional equity. Examples discussed in *SI Appendix*, section S3 demonstrate a shift from using quantitative decision-support tools to compare solutions within a single decision frame (i.e., conception of the nature of the problem, objectives, structure and dynamics of the system, and set of options available)—which often reflects the dominant worldview of status-quo decision-makers and modelers—towards using models to explore the pluralism in worldviews that typically exist for complex sustainability challenges (12, 21). By reflecting this pluralism and incorporating multiple possible worldviews, researchers can better ensure that the interests and perspectives of diverse communities are represented. Quantitative tools from exploratory modeling and multi-criteria decision analysis offer alternatives to aggregation (21, 55, 56) that focus

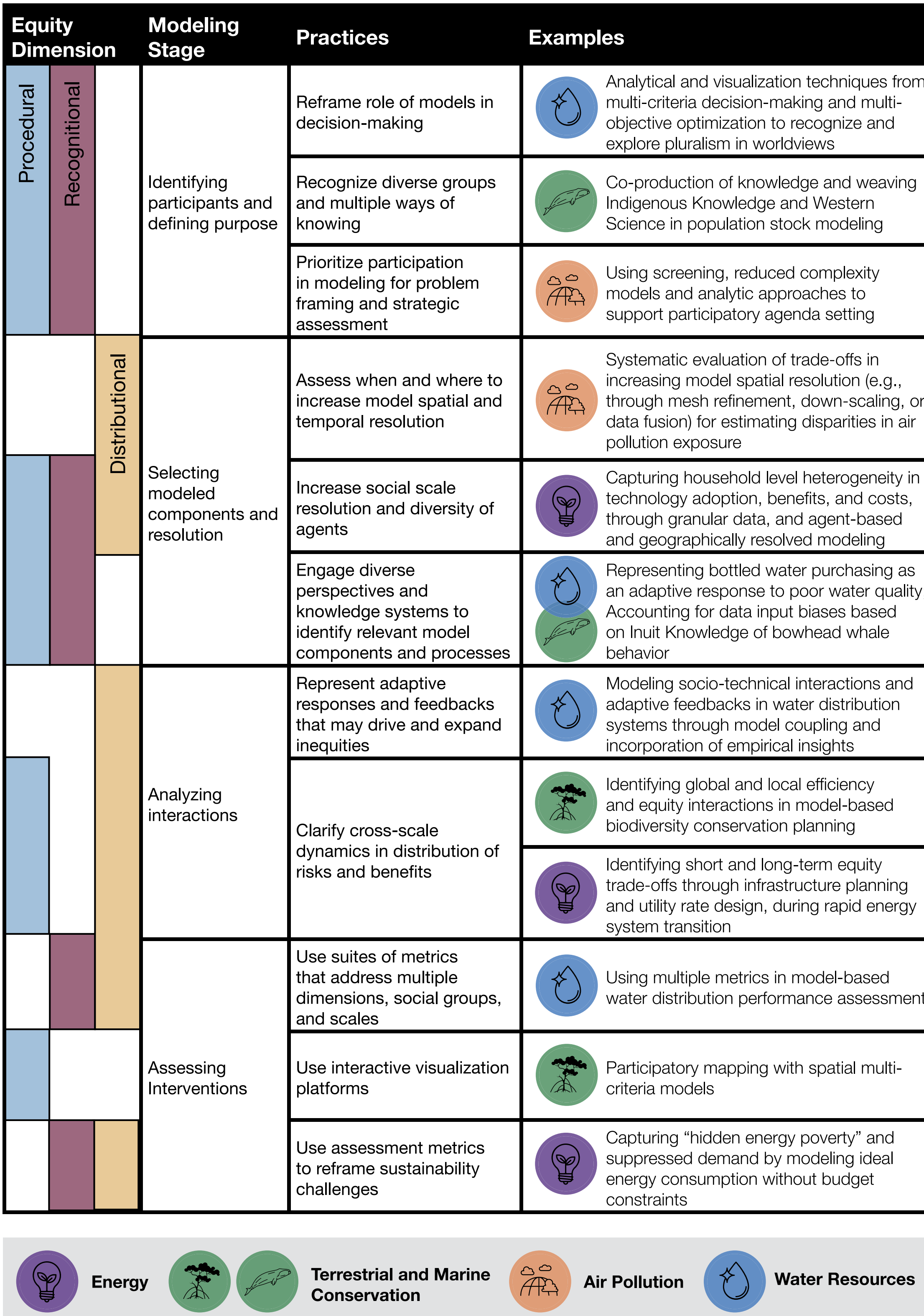

Fig. 1. Summary of examples from throughout the modeling process. Examples of modeling practices that can support procedural, recognitional, and distributional equity, drawn from topical case studies of nature-society sub-systems, which are presented fully in *SI Appendix*. Icons from Teewara soontorn and kareemov, The Noun Project (CC BY 3.0).

on clarifying trade-offs across different objectives and identifying robust strategies across objectives and worldviews. These approaches, combined with visualization techniques such as utopia-dystopia matrices (12), allow for a diversity of perspectives to be analyzed and compared. Applications like these emphasize the role of models as tools for constructive decision aiding and social learning (9, 36).

A more exploratory approach to problem framing also underscores the importance of asking who is involved in decisions about the purpose of modeling and recognizing diverse groups and ways of knowing**.** The example discussed in *SI Appendix*, section S3 points to the multiple worldviews and knowledge systems that can inform marine conservation decision-making (57–59), while also highlighting how conservation decisions have historically not put these ways of knowing on equal footing, resulting in less sustainable outcomes (54, 60). It is critical, in the first stage of any modeling process, for modelers to engage with the broader social and historical context, including the ongoing and legacy impacts of systemic marginalization, such as colonialism. Doing so was a precursor to co-production of knowledge for bowhead whale population modeling and cooperative wildlife management that bridges Western Science and Indigenous Knowledge. This shift emerged through the leadership and advocacy of Alaskan Inuit whalers after the International Whaling Commission suggested a ban on all subsistence hunting that would jeopardize Alaskan Inuit food security, wellbeing, community relationships and ties, and intergenerational transfer of knowledge and culture (61, 62). Williams et al. (27) argue that "acknowledge[ing] positionality and bias" through the practice of critical reflexivity is a key pathway toward equity in modeling. Although scholars from the critical social sciences and humanities have long argued that socio-cultural identity can shape worldviews and research (63), self-reflection on this process is not yet mainstream as part of many modeling workflows. The persistent lack of diversity (including but not limited to gender, racialization, and country of affiliation) in research communities within sustainability science, such as the earth, atmospheric, and ocean sciences (64, 65), climate science (66), and global health (67), further reinforces the need for reflexive practice.

Procedural equity and participation can be prioritized in modeling that supports problem framing and strategic assessment, and the recent focus on developing reduced complexity and screening-level models illustrates how modeling tools can be adapted for this purpose (68, 69). Participation is often only emphasized late in many sustainability decision processes, after strategic choices have already been made and political and financial resources have been committed, resulting in limited ability for participants to influence decisions (70). There is thus a need for modeling that can support participatory problem-framing, agenda-setting, and coalition building, which recognizes that people are experts in their own lived experiences (e.g., ref. 71). For any sustainability-relevant system, there are a spectrum of models (68, 72), and selection of model type and process can be linked to different decision stages. One example presented in *SI Appendix*, section S3 from environmental health modeling is shifting from the more commonly used expert-driven risk assessment toward a community cumulative exposure assessment process to identify strategic priorities using less computationally intensive screening tools (which often use simplified conservative assumptions for upper bound estimates) or analysis methods (e.g., buffer analysis around sources to identify possible exposures) (69, 72, 73). Similarly, reduced complexity models (typically derived from more computationally intensive and detailed models) may allow for more exploratory applications with a larger number of scenarios. These community-engaged modeling exercises can play an important agenda-setting role, to raise questions that need further attention and should be explored in more detail in higher fidelity models.

Selecting Modeled Components. How is heterogeneity across space, time, and social groups represented? What are the underlying assumptions about the structure of the system (e.g., relationships between elements)? Decisions about which elements and linkages within nature-society systems are represented in a model, and at which resolution, have implications for the ability of models to illuminate distributional impacts. Increased interest in assessing distributional equity in nature-society systems has highlighted the need to expand the range and level of granularity of agents and processes (human and non-human) that are represented in models. A lack of procedural and recognitional equity at this stage can also lead to critical omissions in terms of whether and how model components are represented.

Selecting model components with an eye toward equity requires investigations into where, when, and what kinds of granularity should be prioritized in model improvements to meaningfully characterize distributional patterns. Examples of techniques to increase spatial and temporal resolution in air quality modeling include the use of machine learning for data fusion and downscaling, which can bring together process-based models with ground and satellite-based monitoring data (74, 75). Studies have found that lower-resolution representations of nature–society systems often underestimate distributional inequities in air pollution exposure (76, 77). However, there can also be trade-offs in terms of increasing resolution if there are constraints on time and computational resources. Increasing granularity also requires careful consideration of other uncertainties that may be introduced at higher resolutions, given limitations in data or understanding of underlying processes (e.g., emissions misallocation) (78). Systematic evaluations of "how fine is fine enough" for a given modeling purpose in air quality modeling (76, 77), discussed in *SI Appendix*, section S4, point toward the development of best practices as assessment of distributional impacts is becoming a more standard part of air quality modeling analysis (79).

Recent efforts focus not only on representing space and time at finer resolutions but also on increasing granularity in terms of social scale and capturing diversity among people that may exist even within small spatial units (e.g., at the household or individual level). In the context of energy transitions, empirical research has pointed to heterogenous barriers at the household level that lead to distributional inequities in the benefits of energy systems (e.g., access to energy services and clean energy technologies) and their burdens (80–86). The availability of more granular data (e.g., utility bills) and the capabilities to process it are allowing models to better capture these differences and provide insight into which populations are underserved–and enable more tailored interventions (87, 88). Models that represent household-level characteristics, also seen in other sectors (89, 90), illustrate a human-centered approach to equity questions, moving from focusing on environmental characteristics and spatial units of analysis as a proxy for people toward social units of analysis that center human experience. However, increased social-scale resolution also requires attention to questions of trust and privacy, particularly for marginalized communities that have been underserved by, or experienced harm from, past research efforts (e.g., refs. 85, 91, and 92). These issues can present barriers to participatory research processes and data coverage for vulnerable communities (27).

The engagement of knowledge and perspectives from a diversity of disciplines and stakeholders/rightsholders can bring to light components and processes that are important for equity outcomes but which may have previously been omitted by modelers. Broader participation can lead to critical changes in model structure. For instance, dynamic models of climate change adaptation in agriculture systems represent farmer decisions to adopt new farm management practices (e.g., climate-smart irrigation). In certain regions of the United States, such as the Southeast, where large farms are disproportionately owned by White farmers due to socio-economic and policy barriers (e.g., lack of access to credit and capital) faced by Black owners, inequalities in farm size drive trends in irrigation adoption (93). These empirical findings motivate the inclusion of land markets in agent-based models to better capture interacting influences on adoption and their inequitable distribution. Another example is representing bottled water purchasing as an adaptive response to poor water quality in urban settings, as the full burden of water quality degradation is not captured if only modeling the centralized distribution network (94). Finally, *SI Appendix*, section S4 discusses how the inclusion of Inuit Knowledge in population stock modeling for bowhead whales led to revised estimates of an increasing rather than decreasing trend (58, 59). Inuit Knowledge illuminated limitations of count data used as an input given aspects of whale behavior that were not considered in Western Science observations (95).

Analyzing Interactions. When models are applied to "simulat[e] dynamics related to the long-term behavior of systems" (8), how can they be used to illuminate how equity considerations evolve through interactions of components across time and space? Processes that drive, reinforce, and reduce inequity in nature–society systems are dynamically complex, including path-dependencies, cascading impacts, and feedbacks–and these processes are not always well-represented in models. Decisions about system boundaries and initial conditions can also have profound implications for understanding of the above phenomena.

A range of methods are being used to represent adaptive responses and feedbacks within nature–society systems and are beginning to yield insights into processes that drive distributional inequities. Empirical research has identified several dynamics and causal pathways of interest such as: how differential access to information and resources can widen gaps following a shock, exacerbating socioeconomic inequalities (96); how complex cycles of intervention-adaptation in managed systems can lead to unpredictable outcomes with distributional implications (97, 98); and how both autonomous (i.e., reactive) and planned adaptation can result in maladaptation, in which actions taken by an actor/institution shift risk to another space, time, or social group (51). Approaches to better represent these dynamics within models, discussed in *SI Appendix*, section S5, range from developing fully coupled socio-technical or socio-ecological models, where different modeling approaches (e.g., agent-based models to represent differential behavioral responses and engineering models to represent infrastructure systems) are linked (99, 100), to the targeted use of empirical data to parameterize heterogenous impacts based on differential vulnerability or adaptation drivers (101, 102). Across these cases, new datasets are facilitating more sophisticated treatment of adaptation in models; however, care must be taken given structural gaps in these data sets for vulnerable households, and the potential for data to be used in ways that reinforce disparities (e.g., discriminatory screening for services) (90, 96–98).

Model-based analysis can also play a role in clarifying cross-scale (temporal and spatial) dynamics in terms of the distribution of risks and benefits. Many pertinent equity questions in sustainability science concern systems in transition, such as the rapid decarbonization of energy systems, where there may be trade-offs between short- and long-term equity objectives (e.g., who bears the costs of a "utility death spiral" in electrification) (103–107). Similarly, there can be tensions between prioritizing procedural equity and local control and distributive outcomes at larger spatial scales (e.g., in land use decisions) (108, 109). Telecoupling of systems—through trade, human and non-human migration, and other mechanisms—means that interventions to enhance equity in one place may have unpredictable impacts for another (110). These interactions and spillovers across different time horizons and spatial scales point to the multidimensionality of equity and suggest that in many cases, it may be more productive to approach equity "on a spectrum of getting 'more/less' rather than an absolute 'is/is not'" (32). Although it is not always possible to model these interactions explicitly, the examples in *SI Appendix*, section S5 underscore the value of contextualizing the implications of the specific spatial and temporal bounds of analysis and acknowledging the potential limitations of these system boundary choices (29, 111).

Assessing Interventions. How can models be used to assess the equity outcomes of different interventions? One way that models of nature–society systems are used to inform decisions is to compare the impacts of different interventions—whether they take the form of policy, technology, efforts to shape norms and behaviors, or otherwise. The extent to which interventions advance equitable outcomes and process is increasingly recognized as a core assessment metric (e.g., in the UN Environment's Global Environment Outlook) (112). However, defining equity metrics for model-based assessment is a nuanced and iterative task. Equity is a fundamentally normative and multi-faceted concept, and decision contexts can involve multiple (and sometimes contesting) goals, actors and interveners, and time points.

Suites of metrics can clarify degrees, sensitivities, and trade-offs between different dimensions of equity—and across social groups and spatial or temporal scales (113–115). Model-based assessment outputs are thus not an endpoint to decision-making but may instead be a site for broader deliberation in a participatory process (108, 116, 117). To facilitate these uses of models, visualization approaches that allow knowledge users to see multiple metrics and how different interventions may impact them can be particularly powerful (21). Interactive platforms for model building and application—such as CommunityViz (116), En-ROADS and C-ROADS (118), and the Co-Benefits Risk Assessment Health Impacts (COBRA) (119)—can allow for collaborative exploration of potential feedbacks and outcomes of different policy options by adjusting various weights and values. They can also facilitate participatory ground-truthing and validation of model results (29). Participatory assessment processes that use models can also offer opportunities for deliberation around values, means, ends, metrics, and uncertainties, but much like models themselves, must be carefully designed to center equity in its multiple forms (120, 121). For instance, Williams et al. highlight how engagement in multi-actor contexts without attention to power dynamics between stakeholders can yield unintended impacts (27). Explicit acknowledgment of these dynamics and skilled facilitation are possible mitigation strategies (21).

Through the choice of assessment metrics, model-based analysis can be used to reframe sustainability challenges. For instance, in linking emissions and impacts of air and climate pollutants to consumption as well as production (122), model analyses have contributed to reframing ideas of responsibility and brought attention to structural drivers of emissions (123–125). Moreover, metrics based on the most easily accessible data may leave out important aspects of the experience of inequity and reinforce narrow problem framings. Energy poverty metrics based only on expenditures and not unmet or suppressed need mask the true extent and costs of distributional inequities (126). A move toward equity metrics that represent access to services (energy, water, mobility, etc.) as rights and enablers of human agency is consistent with the goal of enhancing well-being—which is in part understood as the capacity for self-determination (127). Although this reframing requires a shift in how some nature–society system models conceptualize and represent actors, recent efforts illustrate how model-based analysis can speak to these questions through incorporation of more granular data that can be used to estimate suppressed demand (e.g., data on air conditioning use in low-income versus wealthy households) and choice of scenarios (e.g., comparing actual energy demand to a case where there are no budget constraints) (126, 128).

Cross-Cutting Themes and Future Directions

Here, we identify common themes and opportunities to advance equity via modeling nature–society systems, drawing insights across modeling in water resources, energy systems, air quality, and conservation.

Models are tools, not solutions. Modeling inherently requires choices of what to model and how, and many relevant phenomena might not be easily captured by these tools. Ultimately, decisions and actions are taken by people. Recognizing this decision support and framing function can broaden understanding of how models might be used in analytic-deliberative processes. For example, models can be a tool to recognize and explore plural worldviews. These worldviews need not be aggregated or consolidated (12, 21, 55, 129). The examples highlight the need for increased recognitional equity in decision-support contexts, as dominant framings from status-quo decision-makers are often treated as the default or the starting point for integrating other perspectives. These might include assumptions about economic growth and progress (130), how humans value nature (131), or the positionality of humans (132). There are opportunities to foster co-production of knowledge based on "an ethic of knowledge co-existence and complementarity" (57) that weaves together different knowledge systems (133). Attention to procedural equity and critical reflexivity on the part of modeling communities about who is participating in modeling efforts is essential (27).

To support decision-making, multiple metrics of equity are needed, as well as innovations in how they are synthesized and presented. Treating equity as a single concept to be optimized to a deterministic end can flatten the complexity of broader social, political, and economic structures and their layered impacts (18), while also obfuscating the ultimate role of model users in making decisions. In many contexts, there can be synergies and tensions across the different dimensions of equity and across different operationalizations of unit (e.g., water quality and water quantity), scope (e.g., which social groups, over which spatial and temporal scales), and preferred shape of distributions. Consequently, another key focus area asks how results from model-based analysis are summarized, visualized, and presented, including whether they are presented as outputs (i.e., a recommendation) versus inputs (i.e., a starting hypothetical to inform discussion). Decisions about how to summarize suites of equity-related metrics, whether through different aggregation functions and composite measures (134), or dashboard approaches (11, 135), are value-laden and may influence decision-making. Practices for promoting care and transparency in acknowledging and unpacking the potentially partial nature of any findings can be shared across modeling communities.

Improved representations of human dimensions and their dynamic evolution are needed to allow nature-society systems models to speak to distributional and procedural equity questions more clearly. These dimensions include behavior; formal and informal institutions; and broader social, political, and economic structures such as racism, colonialism, and incumbency bias that lead to path dependencies (17). Modeling methods such as agent-based modeling can be a valuable tool for capturing heterogeneity in starting points, barriers, enablers, and emergent path dependencies (e.g., widening climate adaptation gaps) (27, 87, 97), particularly when coupled to other modeling tools that can link these insights to broader geographic scales or other impacts. These methods may help illuminate dynamic mechanisms through which vulnerabilities are produced, exacerbated, or reduced. Further, across a range of modeling methods, availability of richer data sets about human and institutional behavior, and computational methods and resources that enable more granular representations, are allowing for deeper exploration of questions of distributive inequities (136). However, the examples in *SI Appendix*, sections S5 and S6 highlight how biases, gaps, and shortcomings in data may influence the kind of models that are able to be articulated, the results of these analyses, and the communities, groups, or individuals for whom these findings may be relevant. Existing datasets may reflect existing biases, with more vulnerable households and communities often being more poorly represented (137). Awareness of these limitations is needed to understand the accuracy and applicability of systems modeling. Here, there may be opportunities to think about modeling and data collection efforts in tandem, and how one can inform the other to improve understanding of equity in nature-society systems.

Data governance can be another site to enact procedural and recognitional justice. Wider adoption of FAIR (Findable, Accessible, Interoperable, Reusable) data principles (138), with respect to data inputs to models, model implementation code, and model outputs, may enable more actors within nature–society systems to use models and their outputs for their goals. For example, there has been new emphasis on developing more accessible and globally applicable open-source tools for assessing air quality impacts (139), such as interactive, web-based source-receptor matrices that allow a wider range of users to lead their own analyses (68, 119). However, making models more accessible is not alone a solution for procedural and recognitional justice. There is also a need to engage with the social context of data: Divorcing data from the social context in which it was collected, generated, and used may reinforce existing disparities in power, agency, and well-being, particularly when communities are not meaningfully involved in shaping protocols around data that describes them (140). Data collected to support improved understanding of inequities may be used to reinforce disparities rather than resolve them: for instance, data on household-level income and expenditures linked to socio-demographic data might be used to determine who to give loans to and at what interest rates. The Global Indigenous Data Alliance's CARE (Collective benefit, Authority to control, Responsibility, and Ethics) principles for Indigenous Data Governance (141) offers an example of pathways toward centering equity and self-determination in the data lifecycle.

One key area for exploration asks how models can uncover and contextualize root cause issues that enable focusing on transforming the systems and structures that lead to harms, rather than merely documenting and proposing strategies to redistribute them (142). An emphasis on documentation can lead to unintended harms from using easily quantified, readily available data (e.g., census demographics, market costs) even when such data are not good theoretic matches (126). The use of wealth or income metrics lead to especially common unintended consequences in cost optimization settings, which may structurally prioritize those with more resources in efforts to protect the greatest "value" as proxied by financial metrics (e.g., in flood prevention and recovery assistance) (21). Similarly, efforts to make models tractable by focusing on areas within the immediate control of a decision maker (e.g., a narrow evaluation of direct impact) can overlook contexts of existing, structural, and interconnected injustices: for example, not considering cumulative burdens when modeling distributive impacts of pollution (143). Instead of focusing solely on harms, we ask how can models both better represent and be better applied to support, the capabilities, agency (127, 144), and desires (145) of communities? The Nature Futures Framework, under the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), offers one example of re-orienting scenario building and modeling to explore transformation toward desired futures (131, 146), with explicit attention to value and knowledge system pluralism in visioning these futures (147).

Recognizing that all modeling methods have their strengths and limitations, there are opportunities to synthesize across different approaches to understand equity in nature–society systems more holistically, including understanding where other methods are needed to complement or replace quantitative model-based analysis. In many quantitative, process-based models of nature–society systems, there are trade-offs between the ability to capture and recognize cumulative and multi-sector impacts (e.g., in integrated assessment modeling, systems dynamics) and the ability to represent these phenomena at high spatial, temporal, and social resolution to capture distributional effects. Likewise, approaches that facilitate high-resolution representation (e.g., agent-based modeling) may come at the cost of transparency and ease of communication, modification, and use—with implications for procedural equity (121). Given these trade-offs, decisions should ideally be informed by iterative learning and synthesis across multiple studies (112). In particular, an overemphasis on quantitative modeling approaches can have adverse equity and sustainability impacts as values and processes that are not easily quantifiable (e.g., in an optimization framework or cost–benefit analysis), or which lack representative data, are omitted (148, 149). Conceptual modeling and qualitative analysis may be more appropriate in these contexts (121, 149). Reflexivity and humility about the limits of quantitative models is necessary for model designers and users alike.

The cases discussed in this Perspective offer examples of how and where models may be useful in illuminating equity in nature–society systems and highlight where key advances are needed to inform decisions toward equitably enhancing human well-being. We conclude by reiterating that our perspective is necessarily partial, and the examples shared in this article are illustrative in nature and not comprehensive. They reflect the experiences of this authorship team, which are not representative of the entire sustainability science community. Our goal here is to contribute to the rich dialog that is occurring in many communities of practice on how models, alongside other tools and approaches, can help societies collectively imagine more equitable and just futures and pathways toward those ends.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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