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Towards integration? Considering social aspects with large-scale computational models for nature-based solutions

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Abstract

Non-Technical Summary. Information on social aspects of climate change intervention, such as behavioral choices and public acceptance, are often not included in global climate models. As a result, they have been critiqued for not adequately reflecting 'real world' conditions. At the same time, these models are important and influential policy tools. To improve these models, calls are being made for more interaction – or integration – between the social science and modelling research communities. Yet, it remains unclear how to achieve this. Responding to this gap, we explore what kind of integration is currently taking place, how, and opportunities for further development.

Technical Summary. The importance of social drivers of climate change interventions, or social aspects, is currently underrepresented in computational modelling projections. These parameters are largely excluded from estimates of technical mitigation potential, feasibility, and tools like integrated assessment models (IAMs) and other large-scale models that influence the development of climate policies and notable bodies like the Intergovernmental Panel on Climate Change. This paper contributes to calls being made within the research community to address this gap and strengthen linkages between modelling practices and social science insights. Using nature-based solutions (NbS) as a framing, we present the results of a critical literature review and interviews with multidisciplinary experts reflecting on the current state of integration around IAMs and opportunities to better capture social aspects within large-scale modelling processes. Our findings confirm the need to incorporate social aspects in IAMs, but highlight that how this happens in practice may depend on context, project objectives, or pragmatic choices rather than conceptual notions about what 'good' integration is. Nevertheless, some integration strategies are better than others, and concerns about data limitations and low capacity of the IAM community for engaging in integration can be overcome with sufficient support and complementary efforts from the broader research community.

Social Media Summary. Integrating social aspects in large-scale models requires complementary efforts from the broader research community.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Climate Change emphasizes that land-based climate change mitigation and emissions reductions are essential, alongside decarbonization of other sectors, to reaching climate targets, and limiting global temperature rise (IPCC, 2019). Thus nature-based solutions (NbS) – actions by people that protect, restore, and strengthen natural ecosystems while addressing societal challenges – have received substantial attention as climate interventions with high mitigation and adaptation potential that also contribute to human well-being and biodiversity goals (Seddon et al., 2021). For example, restoring wetlands can enhance their ability to sequester carbon while improving local water quality and reducing flood risks (Donatti et al., 2022). Similarly, when farmers plant native trees or adopt agroforestry practices they increase soil organic carbon and aboveground biomass while diversifying their sources of income (Augusto & Boča, 2022). Estimates of the technical mitigation potential of these opportunities, however, draw on global, macro-scale modeling with large uncertainties (Griscom et al., 2017), and estimating the socio-economic benefits and tradeoffs is complex (Forster et al., 2020).

As such, increasing attention is being given to the need to better consider social drivers of climate change interventions or social aspects (defined in Section 2.1), in large-scale computational models such as the integrated assessment models (IAMs) dominating the climate pathways assessed by the IPCC (Costanza et al., 2007; Elsawah et al., 2015; Jewell & Cherp, 2020; Trutnevyte et al., 2019). IAMs, for example, are dynamic representations of coupled systems, including energy, land, economic, and climate systems (Weyant, 2017). By combining knowledge of trends and emissions from these sectors, they can be used to make projections about the future and allow us to study the implications of different policies, primarily for climate change. Similarly, large-scale land-use models provide a framework for the assessment of anthropogenic and natural ecosystems at broad, often global, and spatial scales (Munn, 2002).

IAMs have relatively crude representations of land use change but are increasingly being paired with large-scale land use models to allow for higher granularity of analysis and assessment of associated tradeoffs and opportunities. Such land-based IAMs are increasingly being used for national and regional-level assessments, where the need to include social aspects becomes even more apparent. This is demonstrated by recent literature reviews highlighting the variation in land-use decision-makers globally (Malek & Verburg, 2020) and the importance of social factors in the implementation of NbS (Schulte et al., 2021). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has even shifted to a new conceptual framework that puts culture at the forefront of the relationship between people and nature (Díaz et al., 2018).

At the same time, IAMs face a number of limitations. What is computationally feasible may not be on the ground, thus 'feasible' model solutions are often not attainable in the real world (Riahi et al., 2015). Critics also argue it is too easy to generate and 'validate' desired results (Beck & Krueger, 2016), in particular in the face of inevitable uncertainties and when it is only the modelers who make choices about scope, equations, parameter values, and output presentation (Pindyck, 2017). Critical reflection is needed on these choices and related power dynamics. Finally, IAMs generally only represent the views of a subset of actors, for example, those who align with the modelers' values and assumptions (Sonja & Harald, 2018). Yet, these are the ones that are then brought into the policy process, which risks marginalizing and excluding vulnerable groups. This further raises the need for more research on how diverse voices can be brought into the knowledge-making process and how models can better reflect underlying social drivers of climate change mitigation and adaptation decisions.

As such, this paper is guided by the following questions: (1) What is the current state of integration of social aspects and IAMs? and (2) What are opportunities to better include social aspects within large-scale modeling processes? We explore these questions using a critical literature review approach and information elicited from expert interviews with a two-fold aim to first, support a better understanding of integration dynamics within the IAM context that can be useful for researchers; and second, to identify entry points for diversifying perspectives along the modeling process to better inform the stakeholders that can benefit the most from well-balanced IAMs, such as national policymakers, multinational corporations, and international initiatives.

We focus on large-scale computational models, and IAMs in particular, because of the dominant role they have asserted in shaping climate policy and narratives. They have become an important source of information for decision-makers and influential scientific bodies such as the International Governmental Panel on Climate Change (IPCC) in particular, and there is no indication that this will change in the future. The estimated contribution of IAM results to the Fifth Assessment Report of the IPCC (2014) was double that of the First Assessment Report (1990) and the number of publications involving IAMs in the academic literature has exponentially increased over the past three decades (van Beek et al., 2020). In addition, Hughes and Paterson (2017) describe the shift in the IPCC from a body synthesizing knowledge on climate change to an authority on climate change stating that 'the IPCC is defining both the terms of climate change mitigation knowledge production and global political action.' Beck and Mahony (2018) similarly note the influence of the IPCC on the climate policy agenda.

We use nature-based solutions as a framing to limit the scope of our study, which provides us with a useful starting point for identifying literature and experts, and as a lens to reflect on our findings. Additionally, integration is an underresearched, but valuable, topic for NbS and land-use modeling. With NbS it is essential to reflect on multiple system interactions holistically, however, the literature on the interactions between social preferences and large-scale modeling to date has mostly targeted the energy domain and transport sector (Hirt et al., 2020; Krumm et al., 2022; Pettifor et al., 2017; Pye et al., 2021; Sovacool, 2014; Xexakis et al., 2020). Nature has become a serious topic of discussion for climate mitigation and sustainable development in recent years and was one of the key themes at COP26 in the UK. More regional and country-level evaluations of contextual (i.e. non-biophysical and non-technological) factors alongside IAMs are necessary to provide more feasible assessments of opportunities and inform policy planning and options (Schulte et al., 2021). Thus, our findings contribute to ongoing and increasingly urgent methodological and policy research agendas, given the imminent threats of climate disasters, by illustrating the need and possibilities for considering social aspects with large-scale land-based models.

The remainder of this paper is structured as follows: Section 2 outlines the conceptual framework; Section 3 describes our methods; Section 4 presents our findings; Section 5 discusses the implications of our findings; and Section 6 provides our concluding thoughts.

2. Conceptual framework

Here we present the conceptual framework for this paper by defining what we mean by social aspects and integration for the purposes of this study. We use these concepts to guide our research and evaluate our results.

2.1 Defining social aspects

A large body of literature exists that is dedicated to social drivers of climate change. Jorgenson et al. (2019) review this literature and identify factors such as 'economic conditions and development; demographic growth and changes; power, social stratification and inequality; technology; infrastructure; and land-use change' as major contributors to emissions. At the same time, these factors underlie people's responses to policies, potentially influencing how effective efforts are to address climate change and its impacts. Our use of the term 'social drivers' builds on this literature in that we focus on social drivers of mitigation and adaptation activities. Specifically, we are interested in factors in societies and characteristics of people that may influence the uptake of such activities – that is social drivers of climate change interventions.

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For the purposes of this paper, we use terms such as 'social drivers', 'social aspects', 'social preferences,' and 'social factors' interchangeably as these are all terms that have been previously used by authors in the modeling literature. Krumm et al. (2022), for example, define social aspects as 'all aspects that concern the people, their interactions, and relationships within the energy system. [They] use the term as a synonym to social dimension and social factors.' Similarly, Trutnevyte et al. (2019) discuss 'societal factors' that are missing from models. Both studies find that social aspects are not well-represented or integrated in climate change and energy models, and more inter- and transdisciplinary projects are needed. Gerten et al. (2018) outline a set of 'human dimensions' that should be considered in models and propose potential avenues for extending Earth system modeling with sociocultural information, while Moore et al. (2022) introduce these as 'preferences' that can be important for policy and emissions outcomes in models, and thus require multidisciplinary interactions. Studies focusing on integrated assessment models further emphasize the need for integrating diverse perspectives and alternative approaches in those processes that can facilitate exchange and recognize and account for uncertainties (Forster et al., 2020; Keppo et al., 2021; Workman et al., 2020).

Drawing from this compilation of literature, social aspects of particular interest for modeling our behavior and lifestyle choices, the heterogeneity of actors, public acceptance and opposition, public participation and ownership, and transformation dynamics. These are seen as major social processes driving socio-technical transitions (Keppo et al., 2021; Krumm et al., 2022; Trutnevyte et al., 2019). These aspects can influence support or opposition to particular climate interventions or interactions between actors that may lead to cooperation or conflict. Specific social aspects where information is currently lacking in large-scale models include individual and collective behaviors, cultures, perceptions, and values (Gerten et al., 2018; Moore et al., 2022; Workman et al., 2020).

When it comes to nature-based solutions, there is a growing body of literature highlighting the role of social aspects in their planning and implementation. For example, social factors may influence the governance and maintenance of NbS activities; that is how people value rivers or land may impact their motivation to engage with NbS projects (Altieri, 2019; Zingraff-Hamed et al., 2017). Additionally, social aspects such as acceptance of an NbS intervention by Indigenous Peoples and local communities, participation of stakeholders, and recognition of traditional values and norms are among the most frequently mentioned enabling factors for NbS in the peer-reviewed literature (Schulte et al., 2021). Consideration of these social needs and processes can help drive NbS adoption (Donatti et al., 2022). As such, it is important to understand and include these social aspects in research on NbS, such as the development and interpretation of models that may inform policymaking.

2.2 Understanding integration

When it comes to computational models, integration can refer to the technical linking of different models and model components or the inclusion of new elements in the modeling process. Much recent discourse around integration and IAMs has focused on the latter, in particular regarding social science research and models, in an attempt to bring more in social aspects (Krumm et al., 2022; Peng et al., 2021; Trutnevyte et al., 2019). An essential requirement for this type of integration is collaboration between researchers across disciplines. To facilitate such collaboration, Trutnevyte et al. (2019) propose three strategies that, in theory, allow for varying degrees of integration (Figure 1). We use these strategies – bridging, iterating, and merging – as reference points for our research on integration in large-scale modeling processes. The strategies are outlined in detail in the subsequent paragraphs.

Bridging analytical approaches is considered to be the most realistic strategy by many (Geels et al., 2016). This is not a novel approach, and arguably already commonly adopted, even if not formally recognized as such. This strategy consists of collaboration between modelers and social scientists where research occurs in parallel, with opportunities to come together to discuss ideas and promote mutual learning. Bridging these different disciplinary approaches via shared interests and concepts can present a more useful and complete analysis of a complex topic, for example when evaluating sustainability transitions pathways (Turnheim et al., 2015). This is applied by van Sluisveld et al. (2020), for example. The authors use shared concepts to bridge a multi-level perspective framework, which is used for analyzing socio-technical transitions, and IAMs, by allowing researchers to weigh qualitative case-study findings to derive inputs for the quantitative models.

Between the bridging and merging strategies is the iterating strategy. This strategy goes in the direction of approaches that already aim to bring qualitative and quantitative research together in the modeling process, such as the story-and-simulation approach. Here, narrative scenarios are combined with numerical modeling methods to analyze complex causal relationships (Kosow & Gassner, 2007). Social sciences can play an exogenous role in defining narratives, informing model assumptions, or interpreting model outputs. This strategy can be observed with IAMs and the shared socio-economic pathways (SSPs), which are narrative storylines that are used to inform model scenarios and assumptions. They have been designed to allow for iteration and development so they can be adapted to different contexts (Kriegler et al., 2012; O'Neill et al., 2020). Nonetheless, there remains much methodological gray area around iterating strategies and their applications.

Merging is ambitious, but has been critiqued by some as problematic on a fundamental level for epistemic reasons (Geels et al., 2016; Spash, 2012) or undesirable because it detracts from deeper intellectual issues (Castree, 2014, 2015). It involves in-depth, structural modification to a model and assumes key social aspects can be modeled. Even if that were the case and the data was available, altering complex models such as IAMs – that are often developed over a number of years – would require time and effort that is challenging to undertake. Research on vehicle transitions by Pettifor et al. (2017) demonstrates how endogenous changes to IAM formulations that allow for the exploration of social influence and cultural variation do have a significant impact on the model results. However, this still comes with caveats, such as the models still being stylized and utilizing cost-optimal solutions.

2.3 Integration along the modeling process

The modeling process – from scenario development to model utilization – includes multiple stages that may involve different people. These stages are not always independent and there may be overlap between them (Figure 2). Furthermore, important choices are made at each step that shape the final model output.

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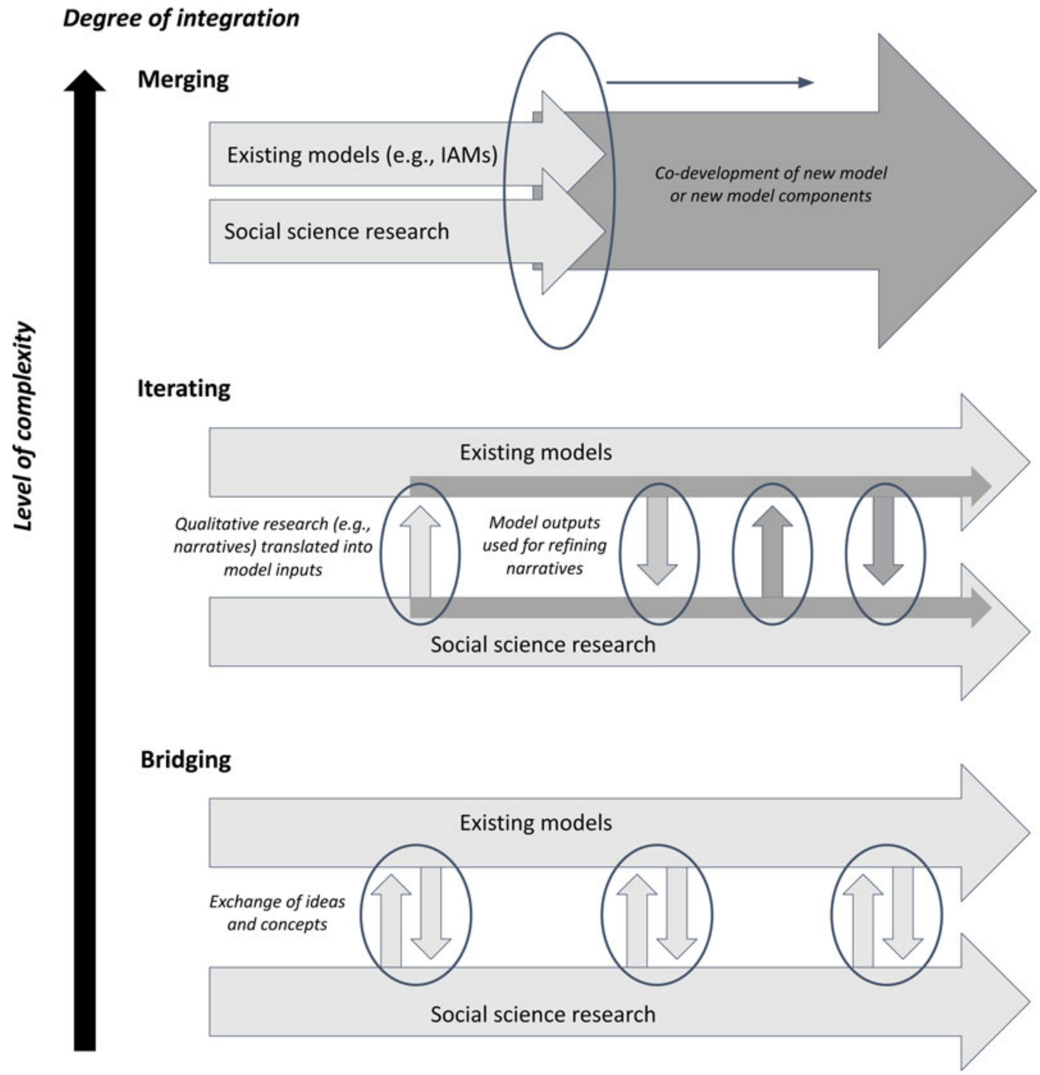

Figure 1. Degrees of integration (adapted from Trutnevyte et al. (2019) and Hirt et al. (2020)).

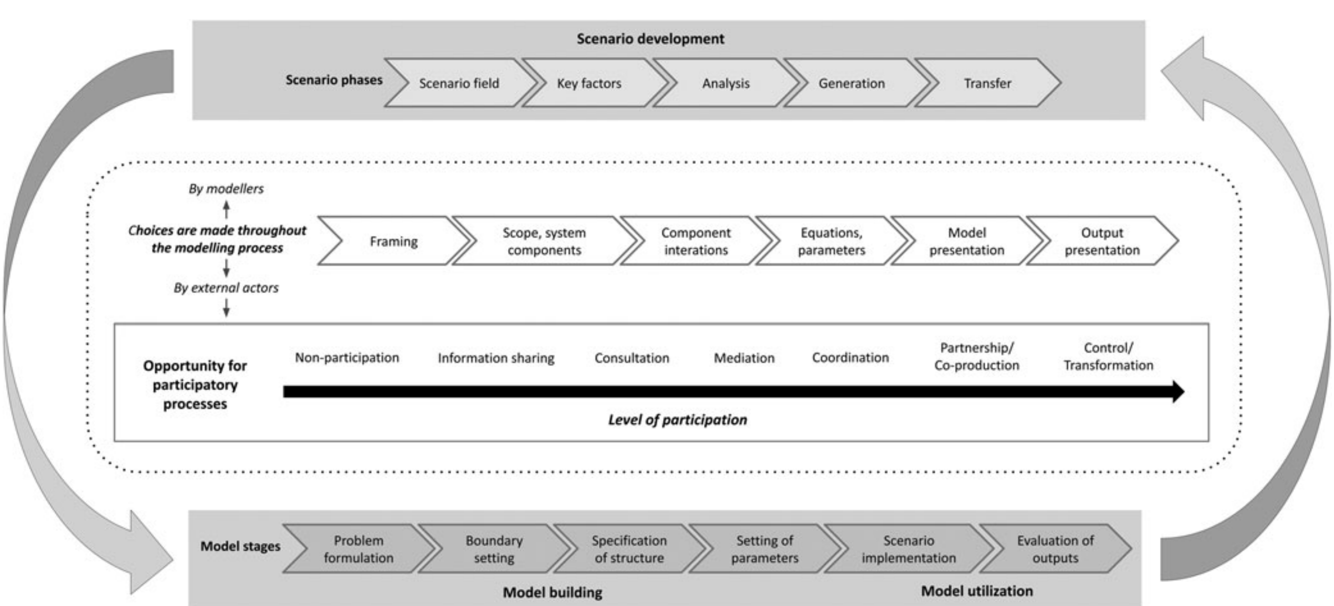

Figure 2. Simplified depiction of the modeling process (own illustration).

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For this reason, as noted in previous sections, there has been a push for the IAM community to include more diverse perspectives in the modeling process. This can happen, for example, via the three integration strategies outlined in Section 2.2. The strategies, as Trutnevyte et al. (2019) present them, primarily consider interactions between researchers of different epistemological backgrounds. Yet, other proposed approaches exist that expand potential engagement to the broader public, such as participatory integrated assessment and exercises that 'open up' social assessments, such as multi-criteria and deliberative mapping (Forster et al., 2020). Additionally, participatory design – particularly with citizens and communities – is a key feature of a holistic nature-based solutions approach (Donatti et al., 2022; Kiss et al., 2022; Puskás et al., 2021; Seddon et al., 2021). These participatory approaches are reflective of broader trends in the scientific process that move toward more radical and innovative forms of knowledge production. This results in a dichotomy between more 'closed' analytic, expert-informed *vs* 'open' participatory, citizen-based assessments (Stirling, 2007). This does not mean that one is more important than the other, but rather it is valuable to recognize the differences and diversity of outcomes that both processes can provide, in particular under conditions of post-normal science.

Funtowicz and Ravetz (1994) argue that post-normal science is necessary when thinking about complex problems with high stakes and large uncertainties, such as global environmental issues. For these issues, traditional, linear research methodologies are not likely to be sufficient for informing decisions, for example for policymaking. New modes of knowledge production recognize the contextual and transdisciplinary nature of science. Additionally, the shift to post-normal science requires new forms of accountability and definitions of scientific quality and reliability that call for input from technical experts, decision-makers, and the public alike (Jasanoff, 2003). The question is, how to effectively enable that broad participation and interaction of different actors to take place. Thinking back to the IAM modeling process, it is important to reflect on who is engaged and when, and who may still be left out and how they could be brought in (Beck & Krueger, 2016). Participatory research theory can be helpful for this (Figure 2).

Specifically, we consider elements from Arnstein's (1969) proposed 'ladder of citizen participation' and a similar typology later developed by Mayer (1997). The former outlines varying levels of participation ranging from forms of non-participation to informing citizens of information, consulting with them, forming partnership, and citizen control. The latter describes seven degrees of stakeholder participation in the policy analysis process, ranging from education and sharing of information, to consultation, anticipation, meditation, co-ordination, co-operation and co-production, and transformation. These levels of participation can provide a framework for understanding who is involved in or should be involved in research processes, including the modeling process, and why.

3. Methods

This work is grounded in a critical literature review and complemented by expert interviews. Our evaluation relies primarily on insights from the literature, while the intention of the interviews was to solicit further perspectives and validate our review. We also elicited information on current thinking and discourses not yet published.

3.1 Critical review

We conducted an in-depth literature review on the topic of integration between social aspects and IAMs. We initially used the Scopus database to search for relevant literature using the query ('integrat*' AND (('social' OR 'societal') AND ('assumptions' OR 'aspects' OR 'dimensions' OR 'aspects' OR 'drivers' OR 'preferences' OR 'factors' OR 'process*')) AND ('integrated assessment model' OR 'large-scale model')). We considered all peer-reviewed, English language literature published in August 2020 or before. The search provided us with 186 results. We selected literature for our study based on their titles and abstracts, using our research questions as guidance. We supplemented this search with additional searches over the course of the development of the study.

As the nature of our review is a critical literature review, and not a systematic review, we did not screen literature using a strict protocol. With a critical literature review approach there is 'no formal requirement to present methods of the search, synthesis and analysis explicitly' as the emphasis is on the 'conceptual contribution of each item' (Grant & Booth, 2009). Furthermore, an 'effective critical review presents, analyses and synthesizes material from diverse sources.' It draws on and evaluates existing literature but may include elements of conceptual innovation, reinterpretation, or resolution of competing ideas. We determined this approach to be most appropriate for the purposes of this research because of the flexibility it allowed us to explore and bring together different bodies of literature. This literature then informed the conceptual framework of our study. In addition, applying a critical review approach challenged us to think creatively about how ideas and learnings could potentially be applied across disciplines.

3.2 Expert interviews

We held 12 semi-structured video interviews with experts between August 2020 and March 2021, following guidance from Dunn (2010) and Longhurst (2010). We identified potential interviewees based on their authorship of relevant papers in our literature searches. We then used the purposive sampling approach from Ritchie et al. (2003) and snowball sampling for our final selection of experts. A heterogeneous sample was chosen to ensure a broad representation of perceptions and experiences. The reason for interviewing experts across disciplines was to understand diverse views on the potential for integration, but also applicability and policy-relevance (Flick, 2009). Specifically, we were interested in speaking to experts working in various capacities and scales along the modeling process and experts with experience researching or collaborating on nature-based solutions projects (Table 1). As such our group of experts was quite multidisciplinary and included conceptual modelers, integrated assessment and large-scale modelers, system dynamicists, and ecologists. While disciplinary backgrounds are included in Table 1, it is worth noting that many interviewees have worked for many years in interdisciplinary contexts. The names and positions of the interviewees remain anonymous. Interviewees are instead referred to by a unique identifier, P1 to P12.

We prepared guiding questions on the researchers' backgrounds, views on the role of social aspects in modeling, engagement with actors and stakeholders, and position on integration of societal information into the modeling process. Our questions were designed to provide vertical depth to the information elicited, starting from conceptual issues (e.g. objectives and ideal methods) to pragmatic research experience. The list of guiding

Table 1. Summary of expert interviewees

Participant	Background	Years of experience	IAM/Large-scale model experience?	NbS experience?	Stakeholder experience?
P1	Policy analysis, energy	30 years	Constructing	No	Yes
P2	Ecology, system dynamics	20 years	Observing	Yes	Yes
P3	Ecology	30 years	Collaborating	Yes	Yes
P4	Physics, earth system sciences	10 years	Constructing	No	No
P5	Systems engineering, policy analysis, energy	9 years	Collaborating	No	Yes
P6	Anthropology, health	40+ years	No	No	Yes
P7	Geography, geoecology, environmental science	12 years	Observing	Yes	Yes
P8	Ecology	15 years	Constructing	Yes	Yes
P9	Natural resource management, system dynamics	40+ years	No	Yes	Yes
P10	Social sciences	14 years	Observing	No	Yes
P11	Climate change policy analysis, tropical ecology	15 years	No	Yes	Yes
P12	Policy analysis, energy, land use, earth system sciences	12 years	Constructing	Yes	Yes

questions can be found in the Supplementary Information. Secondary, follow-up questions were asked impromptu as appropriate (Dunn, 2010). We did not constrain ourselves to this list of questions but adapted as necessary over the course of the interview to allow for a natural flow and create space for more narrative responses (Mason, 2004). Each interview was conducted in English and lasted about 1 hour. We took an interpretive stance for the interviews, meaning our objective was to understand and describe the viewpoints and experiences of different people and groups in real settings (Saldaña, 2015). All interviews were recorded. Following the interviews, information was summarized and key points were transcribed verbatim and coded using MAXQDA. We used the qualitative content analysis (QCA) approach described in Mayring (2014). QCA is a flexible method through which categories of information are inductively coded. We then triangulated the information from the interviews with the narrative synthesis of the literature, using the interviews to validate and critically reflect on the results of the literature review. As such, the interviews provided some external validity to our review and helped to ensure the generalizability and representativeness of our results.

4. Findings

In this section, we present the findings of our review and answer our research questions. We evaluate the questions with our conceptual framework in mind and together with insights derived from our expert interviews.

4.1 Current state of integration of social aspects in IAMs

4.1.1 Calls for more integration between IAMs and social science methods have been the subject of ongoing academic discussion for decades

Easterling (1997) argues that an explicit mechanism was needed to engage stakeholders in the development of IAMs to ensure that their questions are answered and that they can actually use the information that IAMs provide them. Costanza et al. (2007) advocate for the development of more balanced, hybrid modeling approaches that bring together the natural and human aspects of socio-ecological systems. Similarly, Buck (2016) notes that evidence from the ground can provide insights into factors that biophysical and large-scale economic models may be lacking, such as social preferences or inequalities. Jewell and Cherp (2020) suggest that research on these gaps be guided by systematic frameworks. Trutnevyte et al. (2019) concretely capture these calls in a proposed research agenda 'to guide experiments to integrate more insights from social sciences into models.' Similarly, Peng et al. (2021) comment that an IAM reform is needed, to support decision makers in particular.

In practice, while there was a general consensus among the interviewees that there is value in better understanding societal and social aspects that may be drivers of global change, one interviewee mentioned that '*overall demand for integration appears low from the modelling community*' (P4). This interviewee believed that one reason for this is because the community of researchers working on IAMs and other large-scale models is limited in size, though growing rapidly. According to the interviewee, the community is thus limited by the capacities of these modelers, many of whom are working on relevant research to improve other aspects of the models (P4). Supporting this point, two other interviewees argued that IAMs are already linking different aspects of the economy with environmental and climate outcomes over long-term trajectories (P1, P5). Another interviewee who works with IAMs also notes that '[*modellers*] *implicitly represent other social factors through the way that* [*they*] *calibrate the model*' (P12).

4.1.2 Shortcomings of IAMs that can be associated with limited integration of social aspects are widely acknowledged

IAMs primarily take into account economic costs but do not fully address political feasibility (Jewell & Cherp, 2020). Including socio-political constraints, however, could have major impacts on model results and policy implications (Muttitt et al., 2023). Our interviewees confirm this, citing a lack of information such as political incentives, social preferences, and acceptance in large-scale models (P1, P3). Furthermore, IAMs tend to be ineffective at engaging policymakers and stakeholders in modeling activities, if it happens at all (Doukas et al., 2018). There remains little evidence in the literature on the integrated application of multiple methods in modeling (Elsawah et al., 2015). Interviewees familiar with IAMs also recognized the limits of

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their realism (P1, P4, and P7). One noted '*there are parameters that are fixed in the models that we know are not in reality, such as the effect of climate change on rainfall or human behavior*' (P1). From a system dynamics perspective, another interviewee noted '[*these*] *feedbacks are important parts of a model because they affect what people do, and if left out this assumes they have an impact of zero*' (P9).

Overcoming these problems is essential when model-based scenarios are intended for policymaking, as is increasingly the case with IAMs. For scientific activities to effectively contribute to climate policy design they must arguably fulfill three conditions (Doukas et al., 2018): (1) draw from combinations of diverse and complementary modeling tools; (2) adopt a 'demand-driven approach' to modeling activities (e.g. problem formulation, definition of assumptions) that engages all relevant actors; and (3) include methodologies that can be linked with IAMs, which synthesize knowledge from a range of fields, to provide robust and replicable policy advice. These conditions, in particular the second, are also relevant for advancing nature-based solutions; one interviewee states that '*what we're discovering* [...] *about these groups working at the national level* [*is*] *you have grassroots activities going on by community organizations and by, you know, some of these have academics involved, some of them have NGOs involved, local NGOs, but there's nothing in between, connecting. There's no mechanism for really integrating these on-the-ground activities with the higher level*' (P3).

4.1.3 Research on how to more effectively represent social issues in large-scale models is also at different stages for different sectors

Factors related to lifestyle changes, such as shifts in diets and consumption and transportation have been paid more attention than nature-based solutions (Edelenbosch et al., 2018; Fuhrman et al., 2019; McCollum et al., 2018; van den Berg et al., 2019). Nevertheless, modeling behavior is a challenge, because as stated by one interviewee '*you need numbers because those models only work with numbers* [*and*] *it's not easy to translate behavior into numbers*' (P1). For instance, when it comes to nature-based solutions, one interviewee noted that cost and opportunity costs are sometimes included as a feasibility layer and can be a proxy for immediate economic barriers to implementation (P3). The interviewee gave the example that if land has a high return and provides a large profit from agriculture, this poses a major challenge for converting it back into a natural ecosystem.

Though a number of reviews have explored approaches and methods for integrated modeling, these are largely focused on quantifying human–Earth system feedback, and few publications truly bring them together in an applied manner (Calvin & Bond-Lamberty, 2018). Müller-Hansen et al. (2017), for example, provide a comprehensive overview of techniques used to represent human behavior and decision-making in Earth system models; van Vuuren et al. (2012) discuss the strengths and weaknesses of various coupling approaches; Verburg et al. (2016) evaluate the abilities of current models to model Anthropocene dynamics; and Zvoleff and An (2014) present an overview of tools available for analyzing human–landscape interactions. The latter, which also has implications for the modeling of nature-based solutions, highlights that participatory approaches are receiving increased attention when it comes to making the broadest possible data available to information users, such as researchers and policymakers.

The interviews also indicate that there is a shift in the IAM community towards increased interdisciplinary collaboration. The modeling community has put significant effort into linking climate sciences and biodiversity sciences with economics; progress with the social sciences has been slower and some tensions and silos still remain (P1, P4, and P10). In past decades policy and decision-making processes, and even the IPCC, were also more oriented toward economic disciplines and quantitative approaches over the social sciences (P4) (Minx et al., 2017). This highlights an important distinction to be made between 'integrated' modeling in the context of those papers and 'integration'. Integrated models couple existing models so they can exchange information while integration aims for exchange between social science researchers and modelers throughout the modeling process. Far less research to date has focused on the latter.

4.1.4 Consulting with stakeholders in scenario development has been a common way of identifying social aspects for the modeling process

For example, the IAM community has tried and made strides to advance engagement with stakeholders – including citizens and communities – to identify societal considerations through the shared socio-economic pathways. Efforts to expand global SSPs for local, regional, and national use have been ongoing and can provide useful insights on the role of participatory methods and stakeholder engagement in down-scaling large-scale scenarios. Chen et al. (2020), for example, draw on experts' opinions in workshops to identify important drivers of climate change futures in Japan. Frame et al. (2018) constructed and tested narratives with decision makers, stakeholders, and influencers in New Zealand. Similarly, for the Barents region in Russia, Nilsson et al. (2017) used SSPs to guide discussions and co-produce local narratives around future adaptation challenges and Absar and Preston (2015) extended SSPs for the Southeastern United States using a top-down method to create storyline elements for factors, actors, and sectors at the global, national, and subnational levels. These highlight the opportunities for iterative collaboration between modelers and social researchers to ensure that key dimensions, sufficient scalability, and widespread adoption are appropriately considered (Kriegler et al., 2012; O'Neill et al., 2014). Despite advancements in the downscaling of scenario development approaches for SSPs, many studies use arbitrary approaches to select and examine social aspects in IAMs, based on what the expert or modeler may be familiar with (Verburg et al., 2015; Voinov et al., 2018). This can generate dramatically different results between models.

4.2 Ways of enhancing the integration of social aspects in IAMs

4.2.1 Despite calls for integration, it remains unclear exactly how to do this

Some IAMs are top-down computable general equilibrium models, which look to historic macroeconomic trends such as impacts of changes in cost and price as indicators for the future. The issue here is that the past may not capture developments like technological advancements. Agent-based models (ABM) are one approach researchers are looking for integration. ABMs are bottom-up models that can be extremely detailed for certain technologies and can see when there is a maximum gain in efficiency but see less well how demand reacts. Moreover, as noted by an interviewee, these models '*are appropriate for a small scale and more specific questions than IAMs, which are Intended to answer big picture questions*' (P1). Exploration of how to scale up agent-based models is ongoing and holds potential for introducing heterogeneity into large-scale models, particularly at the regional and national levels (Niamir et al., 2020).

Other researchers have suggested turning to social branches of economics such as behavioral, welfare, and political economics (Grubb et al., 2015; Mathias et al., 2020). However, this requires altering the models' methodologies and structure. This was also pointed out by an interviewee: '*deeply incorporating social dynamics and perspectives into IAMs would likely require rethinking some of the foundational economic theory and structure of these models*' (P4). These aspects are not captured in IAMs because they are difficult to model using existing methodological frameworks and may require numbers that are often not available. Without data, it is sometimes possible to determine a suitable proxy or rough substitute measure. One interviewee also argued that an important consideration for using societal data is that it must be '*reliable, in other words, not changing*' for it to make sense to include it in a model (P3).

4.2.2 Any degree of integration needs to consider path dependencies due to methodological consequences of IAM development

The importance of the design of IAMs was highlighted by two interviewees (P1, P9). The diversity of IAMs available illustrates how the choices made in the modeling process fully influence what the model outputs. The results of a model depend on the architecture of the model, including the sectors included and the level of detail. With small-scale models, it is more possible to start from scratch and to engage local stakeholders early on to avoid shortcomings due to path dependency (P7). This is not necessarily always what is wanted or needed for large-scale models (P1, P4, P5, and P7). This poses a challenge for large-scale modeling of nature-based solutions. Since many nature-based solutions projects strive for high levels of participation, for example through consultative and co-production approaches (Puskás et al., 2021), this may be a reason that the literature on social aspects and large-scale models has only had a limited focus on NbS to date.

Furthermore, any model, large-scale models included, can only look like a function of the data they contain. No model is right or wrong, but due to inherent bias in their construction eventually they see different futures, which may have diverging policy implications. For example, most IAMs are linear programming models; they '*assume linear behaviors, and we know that that's not for sure*' (P1). Furthermore, '*they are not exactly dynamic in the sense that you feedback into your model things that already take a bit* [*of time*]' and '*we assume all consumers are rational*' (P1). This is why it is important to have a range of models that can be clustered and discussed with scenarios as is the case in the IPCC assessment.

As such, it is interviewees highlighted the need to be transparent about these models, what they can and cannot do, and how they are designed and carried out; and to do so in a way that is simple and accessible. According to our interviewees – experts who have experience informing, constructing, observing, and interpreting them – it is important to make clear that these models are not trying to forecast anything but to ask 'what if' and envision possible futures (P1, P2, and P5). For example, one interviewee said that researchers can present and instruct policymakers based on the possible implications of some decision that may be taken today, or in the medium or long term, in particular across sectors; in short, they can try to show how sensitive the future is to these decisions (P1).

4.2.3 Stakeholder engagement with clear objectives and an appropriate degree of participation is important for integrating social aspects into models

Lessons from research on nature-based solutions suggest that a higher degree of participation is necessary if modeling to design an intervention or project with a specific area in mind. For example, when it comes to the restoration and management of forests, it is essential to address pressures from adjacent communities (P8). Thus social acceptance and collaboration are key. This engagement is a co-development process. Stakeholders should be involved in the decision-making, implementation, and monitoring process; when they do not agree this may require conflict resolution and mediation (P3). It is also important to be clear about the limits of the research and uncertainties. Tools to simplify models and aid in discussions with stakeholders and their dissemination and accessibility can be useful here (P2, P3, P5, P7). For example, one interviewee with experience working on many NbS projects, suggests to '*find out what the community wants and model it* […] *with better information about expectations, that is where I think you can really get people engaged* […] *put it on a mobile phone or a laptop and let them play around with some of the parameters*' (P3).

In the IAM context, there are varying views of what participation can look like and what gaps participatory approaches can address in models. Sonja and Harald (2018) discuss what elements should be included in IAMs to be able to better contribute to debates about the equity of climate policies. The elements they propose include context sensitivity, increased model responsiveness to user perspectives, and more focus on national modeling that reflects localized socio-economic concerns. Peng et al. (2021) also encourage stakeholders and politically minded researchers to be consulted early in the IAM process and when considering model adjustments to ensure that reforms meet the needs of decision-makers.

It is also important to recognize, however, that a high degree of participation has its limitations. Engagement may be constrained for pragmatic reasons; how researchers practice is often far from ideal due to time or resource bottlenecks (P2, P8, and P10). How study participants are selected also often depends on who is willing to talk to you or where you have a connection. During COVID-19, for example, one interviewee was able to maintain his communications with stakeholders through a local researcher close to the field site (P2). For this reason, interviewees noted there can be advantages to using data that is already available or modeling with a lower degree of participation. In a nature-based solutions context, if there is value to building a relationship with land users for the study this should not be underestimated; however, if the study is a removed or larger-scale assessment, as is often the case with IAMs, and will feed into something that may not impact them directly, it may be prudent to take the existing information and fill gaps as needed (P8). Given a lack of data, external actors can sometimes provide their perception or expert judgment of what data could be (i.e. provide a value for a parameter) (P1, P2). Stakeholders can also be sampled to collect data in a true participatory modeling approach; however, this is more ambitious and again requires additional time and resources (P6, P7).

Beyond the IAM process, we find that systems dynamics and ecological modeling exercises often engage external actors, which we consider to be people who are not part of the internal research team. Some interviewees mentioned that topical or 'social science' experts may be engaged in socioeconomic aspects in modeling work, rather than reaching out to local citizens and stakeholders directly. The primary motivations reported by interviewees for engaging citizens and stakeholders in a modeling process include reducing bias and filling data gaps, increasing the realism of and validating models, and building relationships, concerns which are also relevant to IAMs. There is a need to better understand the position of those who make decisions (e.g. who implement policies) but also the constraints (e.g. political feasibility, social acceptability, and capacity of people to change) (P2). This is consistent with comments from two interviewees mentioning interpretation of results as an area where there is linkage with the social sciences and topical experts may be called upon for input (P3, P6).

At the same time, engaging external actors does not always lead to intended outcomes. One reason for this is because '*what you do in the room with real people* [*e.g. stakeholders*] *cannot often be represented in the models. Either you need to modify the model a lot or you need to make a lot of strong assumptions*' (P5). This reiterates that engagement requires reflection on who is participating, when, and with what aim. In a project assessing various policy mixes, an interviewee reported that the consensus mix that came out of the stakeholder dialogue was quite weak because everything controversial was left out (P10). In another example, the participants of a workshop agreed on the final product, but no one was really satisfied with it (P6). Additionally, a crucial caveat that is very relevant for NbS research is that when engaging external actors, in particular local communities and stakeholders, there is a need to manage expectations at the beginning of the project (P2, P8). There is a risk, for example, if stakeholders expect that you will bring investment or other benefits, they may distort the truth to gain more (P5). Interviewees noted when they succeeded in managing expectations, collaboration and brainstorming were more fruitful.

5. Discussion

It remains unclear how to pursue integration because there is no clear answer. The findings described in the previous section demonstrate that integration often takes place using bridging or iterating strategies to facilitate exchange between modelers and social science researchers. Furthermore, when it comes to nature-based solutions, participatory research approaches are important for engaging stakeholders. Such approaches are also starting to be used to elicit information on social aspects for IAMs, though this may be limited to conceptual change and scenario development and does not always lead to a direct input or structural change to a model. Linking our conceptual framework to our findings can help us interpret some of our results and draw out relevant insights (Figure 3). While interviewees did not explicitly reference participatory theories in their comments, we can use the conceptual framework to reflect on their experiences.

A common thread throughout the interviews with experts who had worked with stakeholders, for example, is that the research objective and goals are important for deciding the level of participation needed. As is often the case with participatory research, the mode or degree of participation is not fixed, and may evolve over the course of a research project. van der Riet (2008) points out that participatory research has the potential to '[access] the intentionality and sociality of human action; and [account] for contextualized and distanciated perspectives in the study of human action.' The ontologies and epistemologies in which the research is embedded in, however, may impact what information is obtained and its validity. Thus, different motivations for participatory research may also tie to different intended outcomes. As one of the interviewees mentioned, the value of engaging communities with nature-based solutions goes beyond influencing choices in the modeling process. It can also strengthen relationships and build trust between researchers and citizens, which may be important to the overall project objective. Alternatively, when an IAM modeler needs to fill a data gap, for example, when deciding how to weigh a parameter, consultation with an expert on the topic may sometimes be sufficient.

As such, our conceptual framework can aid interdisciplinary researchers in deciding on and developing appropriate integration strategies.

Interestingly, a review recently applying Arnstein's (1969) ladder of participation to assess participation in NbS globally. The study finds that while consultation and partnership are the dominant approaches to participation in NbS projects, there remains a need for establishing deeper levels of participation that delegate power to communities (Puskás et al., 2021). While the study looked at many established NbS projects, it is still relevant for the modeling and planning of NbS as it raises an important point about the need to rebalance knowledge production processes for those actors that actually need and use the knowledge. IAMs, for example, have generally been ineffective at engaging policymakers and stakeholders, in part because they do not provide information on the scale these actors need for planning and decision-making. There is a need for more regional and national participation and engagement of actors across the countries that the models represent. To address this need, some national collaborators and users of global models, such as GLOBIOM, have begun to develop regional model versions that can incorporate more country-level data and provide more granular results (Ren et al., 2023; Soterroni et al., 2023).

Finally, our findings also indicate that the current state of integration of social aspects in IAMs is limited for practical reasons, including the lack of capacity of modelers and limited data availability; and epistemological reasons, including differences in IAM and social science research approaches. We offer some possible ways forward (Table 2) and expand on them in the text below along with examples to help illustrate our recommendations.

5.1 Demonstrate support to advance integration

As illustrated in the findings, the limitations of IAMs are widely acknowledged by IAM researchers in the literature. As also mentioned, however, the IAM community is working on challenging and relevant research questions that look at the aggregate, global system and often can already be addressed with the tools available. While it is important for IAMs to move toward being able to answer disaggregated questions about social processes, as these are essential to understanding the implications of NbS, the onus cannot just be on the IAM community to catalyze this shift. On the one hand, funders play a role in soliciting answers to research questions that emphasize integrative work and inclusion of social aspects. On the other hand, the broader community of researchers (e.g. social scientists, complexity scientists, and ecologists) working on NbS topics can also provide an impetus for the IAM community by introducing different ways of thinking and creating demand for integrated research.

One way these disciplinary silos are being bridged in practice is through working groups and consortia where researchers have shared objectives. If a project was interested in the impact of

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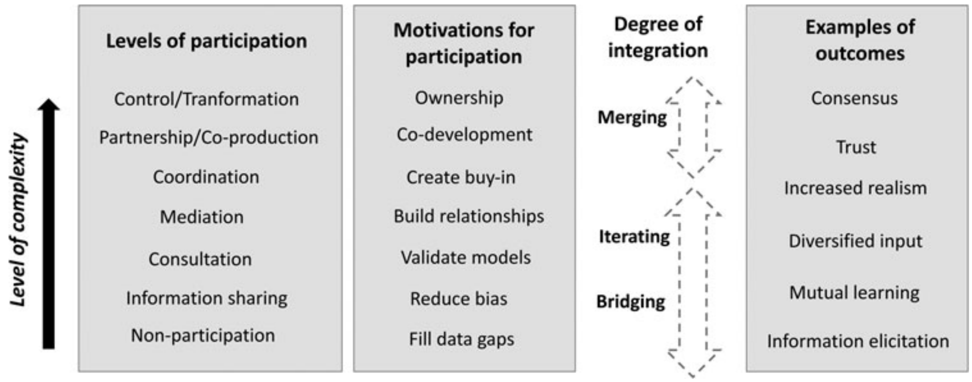

Figure 3. Degrees of integration and participation (own illustration).

conservation policies on a region, for example, in one stream modelers could run different policy scenarios using a large-scale land use model, while in another social scientists could interview actors on the ground about their experiences, perspectives, and activities on the land. The project setting could then provide a bridge for researchers from both workstreams to come together and share results, ideas, and feedback. In some cases, qualitative results can be taken up in the computational modeling exercises, such as by informing constraints, potentially leading to a more iterative integration strategy. Even if results cannot be incorporated, the interdisciplinary discussions and learning are still beneficial for researchers to inform future research ideas, assumptions, and interpretations. Assessment processes such as the IPCC and IPBES demonstrate this on a global scale. Some groups are even going beyond bridging with a merged approach, such as the Large-Scale Behavioral Models of Land Use Change working group of the Global Land Programme. The interdisciplinary group aims to 'support the creation of the next generation of large-scale, land-use change models that take account of human behavior, agency and decision-making processes' (GLP, n.d.).

5.2 Look outside the models for new information

Complementary methods can be used to close remaining questions not answered by IAMs due to a lack of data. For example, one of the most comprehensive and widely known frameworks for systematically analyzing socio-ecological systems is the socio-ecological systems framework (SESF) (Ostrom, 2007, 2009). The framework initially emerged as a tool to assess situations of self-governance and collective action but is increasingly being applied to questions of sustainability more broadly (Partelow, 2018). Applying this to an NbS context, Budiharta et al. (2016) propose an analytical framework for operationalizing a restoration planning approach that accounts for local and contextual dynamics using Elinor Ostrom's social–ecological systems framework and systematic decision-making.

Systematic evidence synthesis methods can also help to address concerns about the reliability of qualitative data. In the field of energy social science, for example, efforts are being made to produce quality computational text analyses (Müller-Hansen et al., 2020). In addition, there are examples of systematic approaches being used to evaluate the effectiveness of NbS and identify stakeholders (Chausson et al., 2020; Zingraff-Hamed et al., 2020), but more research is needed in this area to explore how they can better contribute to IAM processes. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has also made interesting steps in moving forward thinking on values and vested interests in society and for nature, and how to better identify and address them (Díaz et al., 2019). They developed a framework consisting of 18 cross-cutting categories to report on nature's contributions to people (NCPs). This has allowed them to move beyond epistemological differences and bring together diverse types of evidence.

Additionally, external actors are increasingly being consulted to inform model assumptions. Hänsel et al. (2020) use expert views to identify discount rates for economically 'optimal' climate policy paths, which historically have been disagreed upon. Cook-Patton et al. (2020) also approach experts after modeling restoration potential to determine feasibility of different opportunities. Palazzo et al. (2017) worked with regional stakeholders to develop narratives, scenarios, and assumptions about the future of agriculture and food security under climate change in West

Table 2. Challenges to integration and ways forward

Challenges	Ways forward
Lack of capacity of modelers (integration not always a priority)	• Increase enthusiasm and engagement for integration outside the modeling community to create buy-in and incentivize new approaches • Increase funding calls for integrative projects to solidify the importance of integration in research agendas and future workstreams
Lack of information (quantitative and qualitative data)	• Identify complementary research methods (e.g. systematic methods) for addressing data gaps • Engage with external actors (i.e. stakeholders) to inform models assumptions
Epistemological differences (merging not always feasible)	• Use situated modeling exercises to leverage productive tensions and help determine what level of integration is truly needed to answer a research question • Adapt existing models (e.g. IAMs) in parallel to developing new ones

Africa. They then quantified these scenarios using the large-scale, global models GLOBIOM and IMPACT. The RESTORE + project, which is developing scenarios for restoration and sustainable land utilization in Brazil and Indonesia, has similarly been following an iterative approach to integration. Regular meetings with stakeholders were held over multiple years to develop research ideas, present results, and support policy planning. Furthermore, because NbS are highly context-dependent, co-creation and buy-in from stakeholders can be important (Giordano et al., 2020; Zingraff-Hamed et al., 2020). Engagement of stakeholders requires time, but it can enable a more efficient research process as efforts can be focused on more targeted research that is actually needed and wanted by people using the research.

5.3 Be strategic about integration strategies and objectives

While modelers likely know that a merged approach to integration is needed to fully answer their research questions, this is not always pursued. In many cases, iteration may be a more feasible and productive integration approach than trying to create a hard link between research practices, for example by building an entirely new cross-disciplinary model. van Vuuren et al. (2016) argue that in practice, collaboration, rather than a true linking of disciplines, may be the outcome of integration. For example, this could mean working in an inter- and transdisciplinary way to develop research questions and a conceptual idea of an ideal model to decide what model or approach is appropriate to provide information about these questions. By situating the modeling exercise and asking, among a diverse group of experts and stakeholders, why it is taking place in the first place, researchers can assess what kind of integration within the model construct is needed. Future research on this topic could even explore opportunities for collaboration within a formal 'situated modeling' framework, an emerging anthropological concept that seeks to go beyond integration and preserve productive tensions between disciplines (Niewöhner, 2021). Such a framework could be useful for identifying the limitations of computational models and information gaps that could be addressed through research using complementary methods.

There is also value in working to improve existing models, which have been thoughtfully developed by scientists over decades. Integration strategies following a merged approach may determine that existing IAMs are not appropriate for the research question, instead choosing to pursue a different type of model; alternatively, the focus may be on integrating segments of an IAM. In some cases, the latter may be worth pursuing, rather than creating a completely new model from scratch. IAMs are already providing crucial policy insights and an understanding of technological and economic concerns given societally stated preferences like a temperature target (Jewell, 2019). This does not mean that new model development should not also be pursued. Rather, the contribution of IAMs should not be discounted and both approaches should be pursued in parallel.

6. Conclusion

We find that there is a need to incorporate social aspects in IAMs, but how this happens in practice depends on a number of factors. In the end, the choice, type, and extent to which integration occurs may depend on context, project objectives, or pragmatic choices rather than conceptual notions about what 'good' integration is. Participatory research theory can be useful for thinking about what type and degree of integration is needed. For some projects, where citizens and stakeholders may be more directly impacted by the model results or subsequent policy outcomes, deeper participation may be needed. This is often the case for example, with nature-based solutions, where citizens and communities play an integral role in ensuring the long-term success of projects. Future research should explore how integration is operationalized.

As we strive for a more sustainable world, there is a need for research to engage with normative issues and processes (Nielsen et al., 2019). One mechanism for achieving this is through transdisciplinary approaches that enable citizens and stakeholders to be a part of the knowledge production process and drive policy-oriented research. In this study, we have contributed to opening up this space for transdisciplinarity in the large-scale modeling process. Specifically, we provide a conceptual framework that helps advance the integration of social science research and integrated assessment models. In doing so, we respond to calls from the research community for more integration and expand on the existing theoretical literature around integration by linking it to participatory research theory. Furthermore, we unpack bottlenecks to integration and offer a way forward. We place our research on integration in the context of nature-based solutions, drawing lessons from past projects and reflecting on implications for future projects. As such, this work provides an important building block for the generation of integrated knowledge.

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