YSSP Report
Young Scientists Summer Program

Towards the integration of societal factors in large-scale modeling of nature-based solutions

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Approved by

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Abstract

The importance of societal aspects in the implementation of climate interventions, such as the restoration of natural ecosystems, is underrepresented within the current academic literature. To a large extent, these parameters are excluded from the estimates of technical mitigation potential, feasibility, and the tools that inform the development of policies, such as integrated assessment models (IAMs) and other large-scale models. This study aims to explore how data and information on the “contextual” factors (i.e. non-biophysical and non-technological) that influence the uptake of nature-based solutions (NbS) can be better considered in IAMs to contribute to a balanced evaluation of options for implementation. Through literature review and interviews with experts, this research aims to: (1) understand the need for incorporating societal dimensions in integrated assessments; (2) identify opportunities and bottlenecks for integration. Our results confirm our hypothesis that there are different degrees of integration and participation of external actors in the modelling process. These interactions are not fixed; the strategy often depends on the project objectives, and is often influenced by pragmatic instead of conceptual considerations. We conclude by proposing a research agenda for working towards systematic integration under various constraints between large-scale models and the social sciences for NbS.

Keywords: integrated assessment models; large-scale models; nature-based solutions; climate change; social sciences and humanities

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1. Introduction

The emergence of the Anthropocene as a new era recognizing the human influence on biophysical planetary processes demands a science that accepts both coupled and endogenous influences on our Earth system (Kotchen & Young, 2007). The dominant climate change narrative is that the majority of "human" impacts on the environment have been driving a linear increase in anthropogenic greenhouse gases and global average temperatures (Steffen et al., 2018). However, "human" developments – including social, economic, political, and technological factors – are highly uncertain and consist of complex networks of interaction, adaption, and feedback between social systems and natural systems (Henrichs & European Environment Agency, 2007).

At the same time, it is clear that international climate change targets will not be achieved without enhanced carbon sinks, in tandem with efforts to reduce fossil fuel emissions. Concepts such as "nature-based solutions" (NbS) point to the opportunity to shift course by limiting human interference in "natural" processes by protecting and enhancing ecosystems to improve carbon sequestration, while providing human well-being and biodiversity benefits (Seddon et al., 2020). Recent years have seen political momentum around this topic, as evidenced by a growing number of high-level declarations, pledges, and campaigns (e.g. New York Declaration on Forests, Bonn Challenge, United Nations Decade of Restoration, Trillion Trees). Yet, implementation of activities to protect and restore forests and other natural ecosystems remains slow (NYDF Assessment Partners, 2019). Stronger consideration of contextual factors in target-setting and planning processes is essential to effective policy design for restoration and other nature-based solutions.

As such, increasing attention is being given to the need to better consider societal preferences and social processes – "human" dimensions – in integrated assessment models (IAMs) and other large-scale models (Costanza et al., 2007; Elsawah et al., 2015; Jewell & Cherp, 2020; Trutnevyte et al., 2019). IAMs are models that couple economic and climate systems, and can represent emissions from the energy, land use, and other sectors to make projections about the future (Fuhrman et al., 2019; Harfoot et al., 2018). Similarly, large-scale models provide a framework for the assessment of anthropogenic and natural ecosystems at broad, often global, spatial scales (Munn, 2002). For the purposes of this paper, we refer to these models interchangeably, primarily using the term "large-scale models" to encompass both, as IAMs are a subset of large-scale models. These models are an important source of information for decision-makers and influential scientific bodies such as the International Governmental Panel on Climate Change (IPCC).

Nevertheless, integration of the social sciences and integrated assessment models remains limited (Geels et al., 2016; Hirt et al., 2020). Advancements in the scenario development approach of shared socio-economic pathways (SSPs) – alternative narratives of human and natural societies, describing future socio-economic conditions and associated emissions of greenhouse gases – highlight the opportunities for iterative collaboration between modellers 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). Still, many studies use arbitrary approaches to select and examing 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.

Others suggest that integration can be attained through 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. Doing so would also in some cases still require collecting massive amounts of data from participant groups. As such, there remains a large methodological gap around application and evidence of integration of societal information and large-scale models in the literature.

Thus, this work contributes to the emerging research agenda that calls for experiments to integrate more insights from social sciences into models. Our research is guided by the following questions:

- What is the current state of integration of large-scale models and societal information?
- How are external actors, such as topical experts, citizens, and stakeholders, engaged in the modelling process?
- What are opportunties to enhance integration and engage diverse perspectives to better inform stakeholders that could benefit the most from large-scale models (e.g national policy stakeholders, multinational corporations, international initiatives)?

To address these questions, we take an interdisciplinary approach and review diverse theoretical literature and tools, including from systems thinking, ecology, sociology, and public policy; and conduct expert interviews to validate our literature findings and address gaps. We are interested in complementing IAMs and large-scale models for nature-based solutions in particular, as this study is conducted in collaboration with a large-scale participatory project on restoration, RESTORE+, which uses the integrated assessment model, GLOBIOM, downscaled to the national level to analyze dynamics of varying land use policies.

It is also worth noting that we use social-ecological systems as our research entry point, rather than focusing solely on restoration. We do this for two main reasons. First, because this research is not only relevant to restoration but nature-based solutions (NbS) more broadly. With NbS it is essential to reflect on multiple system interactions holistically, as you have local interventions that have global impacts, and so working within the limitations of large-scale models allows us to maintain that perspective. Second, the literature on the interactions between societal factors and large-scale modelling to date has mostly targeted the energy domain (Hirt et al., 2020; Sovacool, 2014; Xexakis et al., 2020). Our study explores potential for linkage, and the relevance of doing so, in social-ecological systems through the lens of nature-based solutions. We argue that varying levels of participation may be needed to achieve varying levels of desired integration. As we aim to reduce the complexity of integration, our desired methodology necessitates a less complex degree of participation. While we limit the scope of this study to large-scale models for nature-based solutions, findings are widely applicable.

In addition, this study makes an important contribution to a crucial methodological gap by proposing and testing an approach to collect information to bridge disciplines and enhance large-scale modeling in a transparent, simple, and systematic way to allow for replicability and comparability. The purpose of this research is no only to improve the models, but also elicit the social issues underlying different pathways to provide decisionmakers better information with fewer uncertainties, for more robust mitigation and sustainable development strategies.

We explore the information needed, from whom, and whether this data is possible to collect without being in the field and by leveraging online research methods, in particular in the context of COVID-19. The findings from this study are also valuable when considering how to do research in areas where there may be limited access, for example areas where it may be difficult to get permission to undertake in-country data collection, or in conflict zones. This may help address some of the geographical bias present climate research (de los Ríos et al., 2018; Lamb et al., 2019).

Our research is presented across two papers. In this paper, which is the first, we present our conceptual framework, hypothesis, and propose a research agenda for integrating information from stakeholders on societal factors in large-scale models of nature-based solutions. In the second paper, we test the hypothesis by developing and applying an experimental systematic methodology, using Indonesia as a case study. The remainder of this paper is structured as follows: Section 1 introduces the problem, motivation, and framing of our research; Section 2 describes the conceptual framework we use to guide our work; Section 3 outlines our methods; Section 4 presents our results; Section 5 provides reflections on the way forward and implications for our next paper.

1.1 Why link societal factors with large-scale models?

Addressing climate change demands transformative solutions and rapid systemic change. Identifying optimal solutions requires working across disciplines and boundaries, and moving beyond scientific norms (Paasche & Österblom, 2019). Despite decades of research on sustainability science, we remain far from achieving a sustainable transition, arguably in part because of siloed ways of thinking and engagement between academics, the public, stakeholders, and policymakers (Shrivastava et al., 2020).

In the case of IAMs and other large-scale models, there is certainly importance to the policy insights and understanding of technological and economic concerns that they provide (Jewell, 2019). However, it is also essential to be transparent about their limitations and bottlenecks to enable the exploration and development of complementary workstreams, as we aim to do with this study. For example, IAMs primarily take into account economic costs, but do not fully address political feasibility (Jewell & Cherp, 2020). What may be 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 (Pindyck, 2017). For example, modellers make choices about scope, equations, parameter values, and output presentation (Beck & Krueger, 2016). Critical reflection is needed on these choices and related power dynamics. IAMs generally only represent a subset of stakeholder views, yet these are the ones that are in turn brought into the policy process. Furthermore, they tend to be ineffective at engaging policymakers and stakeholders in modelling 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 modelling, in particular around such issues (Elsawah et al., 2015). It is essential to overcome these problems when model-based scenarios are intended for policy making, as is often the case with IAMs (Kosow, 2016).

Progress has been shown in efforts to down-scale global SSPs. These include Chen et al. (2020) drawing on experts' opinions in workshops to identify important drivers of climate change futures in Japan and Frame et al. (2018) in New Zealand constructing and testing narratives with decision makers, stakeholders, and influencers in workshops. 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 & Preston (2015) extended SSPs for the United States Southeast using a top-down method to create storyline elements for factors, actors, and sectors at the global, national, and subnational levels.

There is an opportunity to enrich and validate social and economic data by eliciting perspectives of diverse stakeholders (Krueger et al., 2012; Norrman et al., 2020), and a need to develop methodologies to move beyond individual case studies and to do so at scale. Though onerous, there are good reasons to do this including interdisciplinary learning and collaboration between different analytical communities, increased realism of models, and enhancing information on societal factors to accompany model pathways (Hamilton et al., 2015).

1.2 Socio-ecological systems as an entry point

While the restoration of natural ecosystems has a high mitigation potential, research on the feasibility or potential of restoration is often limited to a techno-economic or biophysical assessment (Acosta et al., 2018). Estimates of the technical mitigation potential of these opportunities draw on global, macro-scale modelling with large uncertainties (Griscom et al., 2017), and estimating the socio-economic benefits and tradeoffs is complex (Forster et al., 2020). More regional and country-level evaluation is necessary to provide more feasible assessment of opportunities and inform policy planning and options. This requires that more consideration be given to cultural, social, technical, and political dimensions that influence the outcomes of NbS activities, such as restoration (Pandit et al., 2020).

These cross-cutting dimensions of NbS and planning and accounting for anthropogenic changes to earth system dynamics requires rigorous, integrated socio-environmental, or socio-ecological, systems (SES) research approaches. A socio-environmental system is defined as "a coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner" (Redman et al., 2004). Models must connect social and biophysical dimensions if we are to even try to illustrate Anthropocene dynamics (Costanza et al., 2007). This calls for better climate models that systematically and robustly integrate societal dynamics.

Yet, a prominent challenge in modelling SES is how to incorporate human dimensions that influence these systems. Efforts to improve the meaningful representation of these dimensions are nascent (Elsawah et al., 2015). Current models representing scenarios of environmental and climate change, including IAMs or national or biome-level assessments (Dyer et al., 2017; Fink et al., 2020), do not reflect societal influences and interactions and are limited by epistemological and ontological differences between different disciplines (Verburg et al., 2016). More work is needed on how to bring qualitative and quantitative methods together and how to use methods from different disciplines in complementary ways. New, transparent approaches are needed to assess feasibility that account for broader perspectives, issues, and uncertainties (Stirling & Mayer, 2001). This does not require novel scientific methods, but using existing methods in novel ways.

An overarching hurdle, and strength, of SES research is the interdisciplinary nature (Miller et al., 2008). Scholars from diverse disciplinary backgrounds and trainings are expected to come together, which may lead to misunderstandings or disagreements in framing, evidence, and approach (Beck & Krueger, 2016). For example, researchers from different backgrounds (e.g. social science vs. natural science) may have conflicting ideas about what constitutes valid and quality data or results, including collection and analysis tools (Verburg et al., 2016).

2. Conceptual framework

2.1 Degrees of integration

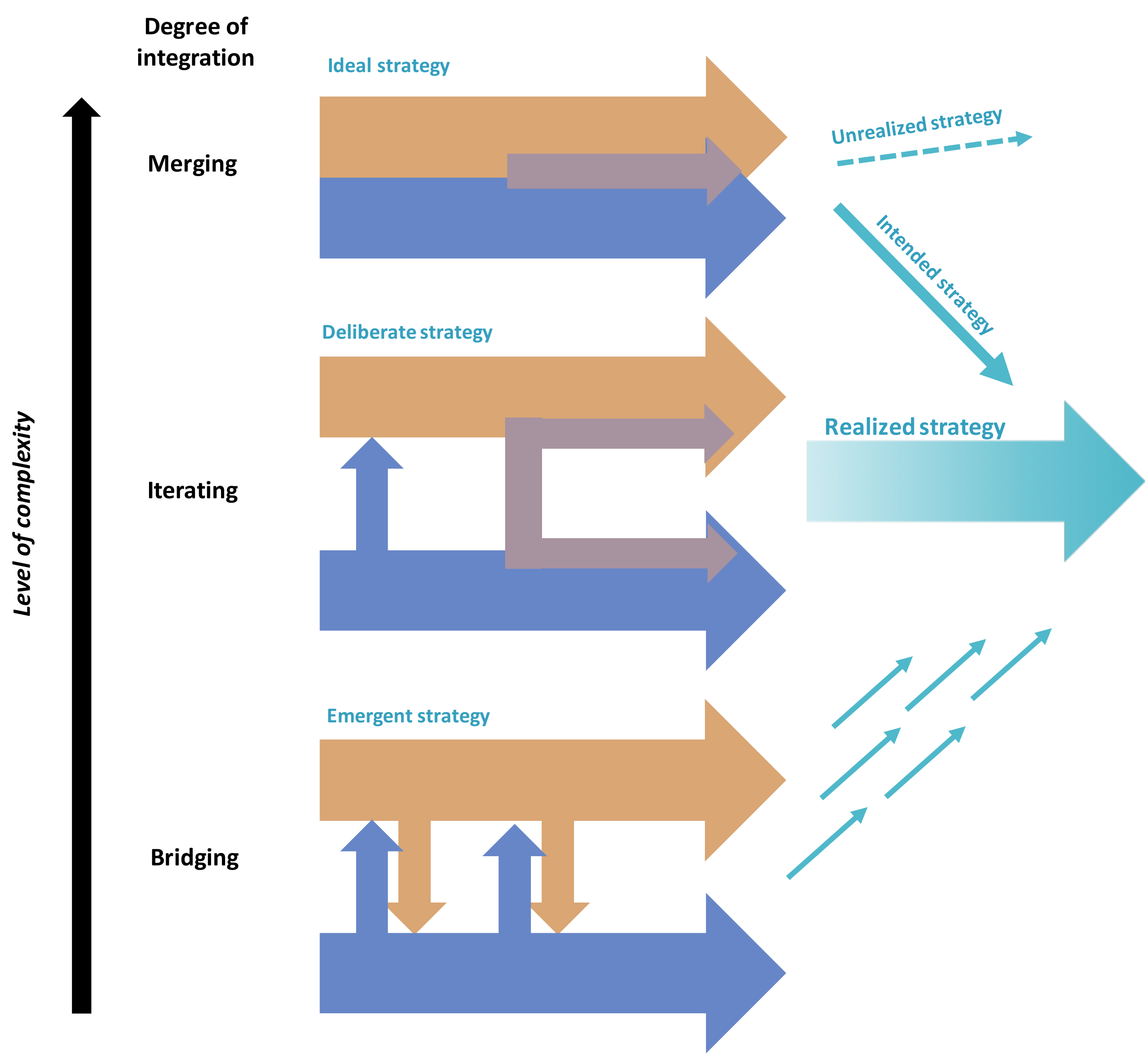
Integrated assessment models present a simplied view of complex systems. The nuances not represented by IAMs are often the underlying factors that ultimately reflect the feasibility of implementing a given policy. While IAMs are influential, valuable basis for climate policy decisions and critical to mitigation pathways analysis, presenting adequate real-world policies and processes requires enhancing large-scale models with other approaches (Gambhir et al., 2019). As such, there is an ongoing discourse around linking IAMs with the social sciences (Geels et al., 2016; Trutnevyte et al., 2019). Calls for integration between these approaches range from “bridging” strategies, where information is exchanged while research continues in siloes to “merging”, which involves in-depth, structural modification to a model (**Figure 1**).

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 represents collaboration between modellers 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 on a complex topic, for example when evaluating sustainability transitions pathways (Turnheim et al., 2015).

Merging is ambitious, but has been critiqued by some as problematic on a fundamental level for epistemic reasons (Geels et al., 2016) or undesirable because it detracts from deeper intellectual issues (Castree, 2014, 2015). This strategy assumes key societal factors can be modelled; and even if that were the case and the data was available, altering these complex models – that are often developed over a number of years – would require time and effort that would be challenging to undertake.

Between the bridging and merging strategies is an “iterating” strategy (Trutnevyte et al., 2019). This strategy goes in the direction of approaches that already aim to bring qualitative and quantitative research together in the modelling process, such as the story-and-simulation approach. Here, narrative scenarios are combined with numerical modeling methods to analyze complex causual relationships (Kosow & Gassner, 2007), for example, by identifying and weighting the influential elements in a system. The social sciences can play an exogenous role in defining narratives, informing model assumptions, or interpreting model outputs. Nonetheless, there remains much methodological grey area around types of iterating strategies and their application.

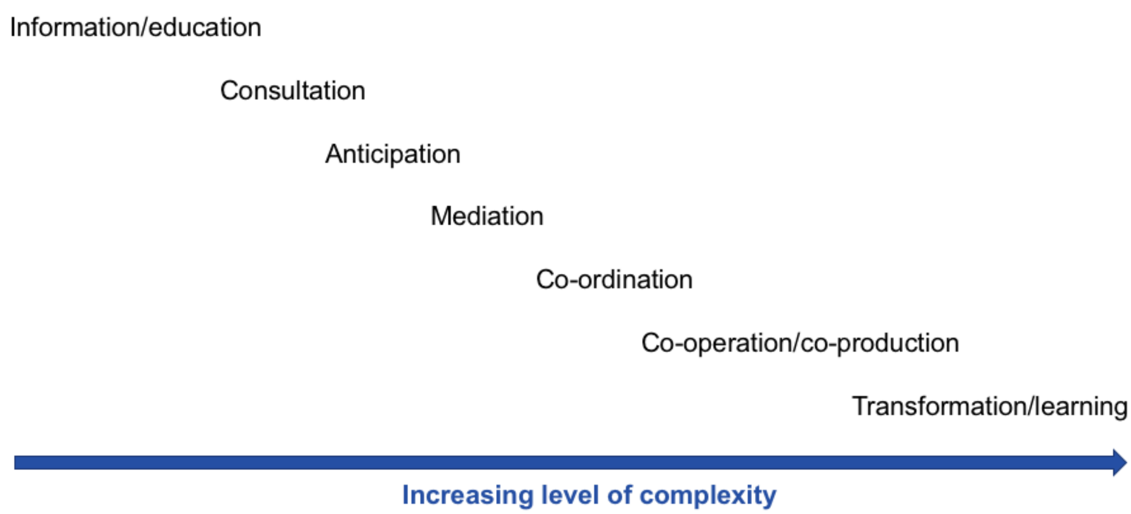
Figure 1. Degrees of integration (adapted from Trutnevyte et al. (2019) and Geels et al. (2016))



2.2 Degrees of participation

Participatory research can be understood as "a process of sequential reflection and action, carried out with and by local people rather than on them" (Cornwall & Jewkes, 1995). As such, an important advantage of participatory research is the rebalancing of power between the researcher and those researched on. At the same time, there is a lack of consensus around what this means and how it is executed. Arnstein (1969) first proposed a “ladder of citizen participation” that inspired a typology that included levels of passive participation, extraction of information, decision-support participation, interactive participation, and self-organization of participants (Pretty, 1995). This was later narrowed down by Lynam et al. (2007) to extractive use, co-learning, and co-management of knowledge for a decision-making process. Similarly, Mayer (1997) outlined seven degrees of “stakeholder” participation in the policy analysis process. While these degrees are non-linear, they do increase in complexity, or the engagement required from actors. In all cases, the mode or degree of participation is not fixed, and may evolve over the course of a research project (**Figure 2**).

Figure 2. Degrees of participation (adapted from Mayer (1997))



In line with the literature, we argue that there is no inherent greater value in one type of participation over another, but the degree of participation ultimately depends on the research and overall project objectives. The involvement of stakeholders in model-based research can benefit from good practice guidelines, which can also be selectively applied to our study (Korfmacher, 2001). These include:

- Transparent modeling process
- Continuous involvement
- Appropriately representative involvement
- Influence on modeling decisions
- Clear role of modeling

For example, despite recent popularity of co-production in research, this may not always be appropriate (Kosow, 2016). In addition, truly achieving co-production is challenging due to the level of effort and resources needed (Boivin et al., 2014; Bovaird & Loeffler, 2012). As our intended systematic methodology aims to reduce complexity of engaging stakeholders to increase the realism of models on the national level, and not design local-level interventions, a degree of participation at the level of “consultation” is likely sufficient.

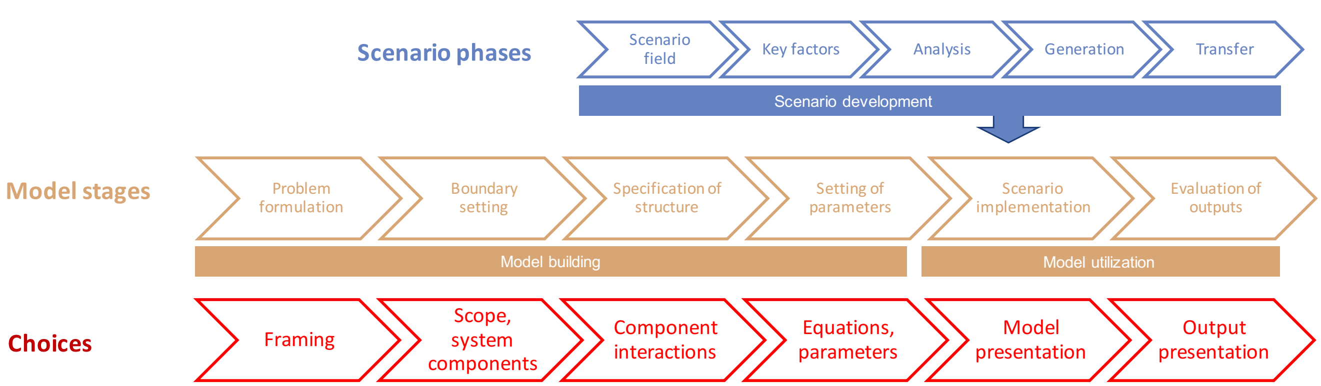
2.3 Hypothesis

There is much to be gained by better representing socio-environmental systems in large-scale models. For scientific activities to effectively contribute to climate policy design they must arguably fulfil three conditions (Doukas et al., 2018): (1) draw from combinations of diverse and complementary modelling tools; (2) adopt a "demand-driven approach" to modelling activities (e.g. problem formulation, definition of assumptions) that engages around all relevant actors; and (3) include methodologies that can be linked with IAMs, which synthesize knowledge from a broad range of fields (Kelly (Letcher) et al., 2013), to provide robust and replicable policy advice.

Our literature review on the state of research linking social science methodologies, in particular, with IAMs (**Section 2.1**), suggests that this area of research remains underexplored. As such, we see significant potential to contribute. We see the merging strategy as the ideal degree of integration, but unrealistic for pragmatic reasons when it comes to large-scale models. Thus, we anticiptate our approach will fall within the iterating range of strategies.

Reflecting on the participation literature (**Section 2.2**), we hypothesize that different degrees and combinations of citzen, stakeholder, and expert participation are relevant at different stages scenario and model development, and contingent on the project objectives (**Figure 3**). The is not always a fixed process, and these may be overlap between phases and stages. Important to consider are also the choices made throughout the process, and the actors involved. For our purposes, we envision integrating information on societal preferences during scenario development and model utilization, rather than model building. Eliciting information from diverse actors at these points will allow us to map the assumptions going into the model, analyze how they relate to realities on-the-ground, and help to identify missing societal factors in the model (Hölscher et al., 2019). While using an iterative strategy to improve our understanding and model utilization means we may not fully endogenize societal insights, we argue it is also a step towards providing a more balanced picture of the situation and alleviating some of the potential bias that may arise when translating IAM and large-scale model results into national policy recommendations.

Figure 3. Simplified depiction of the modelling process



3. Methods

We considered literature on the methodological gaps and limitations of integrated assessment models and reviewed scientific literature to provide the theoretical framing for our study. We drew from a range of disciplines due to the interdisciplinary nature of this research. Literature on integrating social perspectives with models and participation in research and policy analysis provide the basis for our hypothesis. In addition, we consulted literature on the regional expansion of global shared socio-economic pathways as a first step in the validation of our hypothesis. The rationale for this is that 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. These insights were confirmed or adapted based on interviews with experts, which was the second step in our hypothesis validation.

We conducted ten semi-structured video interviews in total between August and October 2020 (Dunn, 2010; Longhurst, 2010). The intention was to gain better insight into the approaches and difficulties of linking societal data with large-scale models. We also elicited information on current thinking and discourses that may not yet be published. We used a purposive sampling approach for our selection of experts (Ritchie et al., 2003). Experts were selected based on their first authorship or co-authorship (on papers with only two authors) of publications deemed relevant to this study, with further experts selected via snowball sampling. A heterogeneous sample was chosen to ensure 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 modelling process. As such our group of experts was quite multidisciplinary and included conceptual modellers, integrated assessment and large-scale modellers, system dynamicists, and ecologists (**Table 1**). Whille disciplinary backgrounds are included in the summary table, 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 referred to by a unique identifier, P1 to P10.

Table 1. Summary of interview participants

Participant	Background	Years of experience	IAM/Large-scale model experience?	Stakeholder experience?
P1	Policy analysis, energy	30 years	Constructing	Yes
P2	Ecology, system dynamics	20 years	Observing	Yes
P3	Ecology	30 years	Collaborating	Yes
P4	Physics, earth system sciences	10 years	Constructing	No
P5	Systems engineering, policy analysis, energy	9 years	Collaborating	Yes
P6	Anthropology, health	40+ years	No	Yes

P7	Geography, geoecology, environmental science	12 years	Observing	Yes
P8	Ecology	15 years	Constructing	Yes
P9	Natural resource management, system dynamics	40+ years	No	Yes
P10	Social sciences	14 years	Observing	Yes

We prepared guiding questions on the researchers' backgrounds, views on the role of social references in modelling, engagement with actors and stakeholders, and position on integration of societal information into the modelling 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 questions can be found in the **Annex**. 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 lasted about one hour. We take an interpretive stance for the interviews, meaning our objective is to understand and describe the viewpoints and experiences of different people and groups in real settings (Saldaña, 2015). Interviews were recorded, transcribed, and coded with similar responses grouped by theme.

4. Results

4.1 Current state of integration

Here, we describe our results on integration throughout the modelling process, organized by gaps identified through our interviews, as well as challenges such as the design of IAMs, technical limitations, and disciplinary tensions. An alternative presention of the results could be to discuss the state of integration at each stages of the modelling process. While we have not done this here, we can consider adjusting this for future versions of the paper.

4.1.1 Gaps

The results of our interviews with experts from across relevant disciplines indicate that **there is a clear gap in certain types of societal information**, such as political incentives, social preferences, and acceptance, in large-scale models (P1, P3). Cost and opportunity costs are sometimes included as a feasibility layer and can be a proxy for immediate economic barriers to implementing a nature-based solution (P3). For example, 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. Agent-based models are another way these issues may be considered, but these models are appropriate for a small scale and more specific questions than IAMs, which are intended to answer big picture questions (P1).

As such, discussions on if and how this gap can be filled are tied to the fundamental question, what is the purpose of these large-scale models? 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, P5). In doing so, 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 (P1); in short, they try to show how sensitive the future is to these decisions.

In addition, many of the interviewees familiar with IAMs recognize the **limits of their realism** (P1, P4, P7). 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). These feedbacks are not captured in the model because they are difficult to model and it requires numbers that are often not available. Without data, it is sometimes possible to determine a suitable proxy or rough substitute measure. From a system dynamics perspective, 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). Thus, identifying these gaps can help pinpoint research needs.

4.1.2 Design and choices

The design of IAMs was highlighted by two interviewees (P1, P9). The diversity of IAMs available illustrates how **the choices made in the modelling process** wholey 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. 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. Others are bottom-up models, and extremely detailed for certain technologies and can see when there is a maximum gain in efficiency, but see less well how demand reacts.

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. 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.

4.1.3 Technical limitations

While there was general consensus among the interviewees that there is value to better understanding societal and human dimensions that may be drivers of global change, one interviewee mentioned that **overall demand for integration appears low** from both the modelling community. Integrated assessment models are already doing an excellent job of linking different aspects of the economy with environmental and climate outcomes over long-term trajectories (P1, P4, P5). The community of researchers working on IAMs and other large-scale models is limited in size, though growing rapidly, and thus limited by the capacities of these modellers. Many of them are already busy working on relevant research to improve other aspects of the models.

Furthermore, deeply incorporating social dynamics and perspectives into IAMs would likely require rethinking some of the foundational economic theory and structure of these models (P4). With small-scale models, it is more possible to start from scratch, and to engage local stakeholders early on to avoid path dependency (P7). This is not what is wanted, or needed for large-scale models (P1, P4, P5, P7). This is why it is important to **be transparent** about these models, what they can and can't do, and how they are designed and carried out; and to do so in a way that is simple and accessible (see **Section 4.3.3**).

4.1.4 Disciplinary tensions

Our interviews confirm that there is a shift in the IAM community towards increased interdisciplinary collaboration. The modellling 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, P10). In past decades policy and decision-making processes, and even the IPCC, were also more oriented towards economic disciplines and quantative approaches over the social sciences.

4.2 Engagement of external actors

The results in this section are not limited to interviewees' experiences, if any, with engaging external actors in the IAM process. Rather, we draw from their diverse backgrounds and elicit information eliciting social information to inform various scales and types of models, including systems dynamics and ecological modelling exercises. Furthermore, we focus our results on the engagement of external actors, which we consider to be people that are not part of the internal research team. We do this because some interviewees mentioned that topical or "social science" experts may be engaged on socioeconomic aspects in modelling work, rather than reaching out to local citizens and stakeholders directly.

4.2.1 Motivations

The primary motivations reported by interviewees for engaging citizens and stakeholders in a modelling process include **reducing bias and filling data gaps, increasing the realism of and validating models, and building relationships**. 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 feasiblilty, social acceptability, capacity of people to change) (P2).

Overall, how experts and stakeholders are engaged in any modelling processes depends on the context and objectives of the study. Interviewees experienced with these types of engagement described the interactions in a way that can be categorized as either **participatory, consultative, or a combination**. The type and extent of engagement varied by project and the motivation for engagement. An interviewee described working together with stakeholders over two years to develop plausible, coherent, and consenus scenarios for the future; in another study, her interactions were much more limited and technical, as she just needed someone who could tell her something about policy interactions (P10).

4.2.2 Outcomes

The benefits of engagement with external actors include **elements of trust, consensus, exchange, learning, and information elicitation**. Workshops are commonly used to gather and engage people. Some workshops are failures for information and data elicitation, but can be powerful for building trust (P2). In particular, when it comes to understanding system you can still learn about conflicts, the position of stakeholders, and even where there may be apprehension towards researchers. Many interviewees noted they observed participants and themselves sometimes even changing their position in these circumstances, or overcoming prejudices towards each other (P2, P5, P10).

In various project examples, experts or stakeholders were consulted on important factors in a system, what to include in models, if they agree with model assumptions, and so on (P1, P6, P8, P9, P10). This also depends on the technical literacy of the external actors. In an ideal case, time would be spent working with partipants to **enhance their understanding** to allow for informed decisions or they can mandate ane expert to represent their views. The modeller would **negotiate** with them until a consensus was reached. This process itself also creates transparency and helps to identify points in a model that are crucial and controversial.

Similiarly, almost all of the interviewees described their work as involving **iteration, though at different stages**. Depending on the project, this could be an iterative exchange with fellow co-researchers at the beginning of the research process, during the analysis, or an exchange with the stakeholders being engaged. This could mean, for example, going back to stakeholders after initial discussions and presenting them with model results to confirm that they are in line with their thinking or see where adjustments may be needed (P1, P2, P7, P8, P9, P10).

A crucial caveat when engaging external actors, in particular local communities and stakeholders, is the need to **manage expectations** at the beginning of the project (P2, P8). There is a risk, for example, if stakeholders expect that you'll bring investment or other benefits they may distort the truth to gain more (P5). Interviewees noted when they succeeded in managing expectiations, collaboration and brainstorming were more fruitful.

4.2.3 Conditions

At the same time, engaging external actors did not always lead to intended outcomes. 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; it would be feasible to implement, since there is agreement, but everything negative was left out, as was everything effective (P10). In another example, the participants of a workshop agreed on the final product, but no one was really satisfied with it (P6).

A **higher degree of participation** is necessary if modelling to design an intervention or project with a specific area in mind. For example, when it comes to the restoration and management of forests pressures from adjacent communties are essential to address, thus social acceptance and collaboration are key (P8). 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 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, 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, there can be advantages to using data that is already available or modelling with a lower degree of participation. If it is 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, like IAMs, that 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 judgement 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 modelling approach; however, this is more ambitious and again requires additional time and resources (P6, P7).

4.3 Opportunties to enhance integration

The results of our interviews find ongoing areas of integration in all phases of the modelling process – scenario development, model building, and model utilization – that can be further enhanced. We again draw on insights from the interviewees experiences that go beyond large-scale models, but can provide applicable insights nonetheless.

4.3.1 Framing

Several interviewees cited examples where multidisciplinary group came together **to frame a study** (P1, P3, P5). In one example, an interviewee described a process where social scientists came together to support the selection of socioeconomic variables for the creation of a new model (P3). The social scientists proposed an initial list, while the modelling team then determined which variable from the list were attainable based on the literature, raw databases, and existing maps.

Here there can be a difference between discussions on **desired and expected states** of the world (P5). Both are useful; but it is important to clarify which is sought. Global scenarios informing IAMs, like the SSPs, are generated by the expert community rather than stakeholders and reflect plausible states of the world based on their knowledge. In national planning, for example, people might have stronger opinions on their desired state of the world and models should take this into account. In latter, there is a dynamic component that traces relationships between actors and incorporates their views on a system to ensure it is logically consistent, and based on that more detailed narratives can be developed for a specific problem.

4.3.2 Modelling

Experts from the social sciences and stakeholders can also collaborate with modellers in model building **without requiring a complex redesign** of a model, for example in setting boundary conditions or deciding which parameters to include (P2, P3). This may be embedded in scenarios, such as the SSPs. It is relevant to improve the realism of these elements of the model in particular, as small-scale modellers often use global modelling exercises to frame their systems and align their more localized models with the large-scale context.

Adding a module to a model is possible if data is available and the modellers are willing (P1). Another consideration for societal data is that it must be **reliable** for it to make sense to include it in a model (P3). This means, if there is data available and it does not change from year to year, then it might be possible to incorporate it. However, if the data is just from one year, or will not be relevant for the future, then it may make sense to use it to help interpret some of the other trends in the models or identify where there may be need for targeted research and in-depth SES analysis to understand these uncertainties – for example issues related to food security, political safety, or social unrest – and if the conditions are really adequate to push for nature-based solutions there.

In that case, using restoration as an example, it might make sense to model where restoration could be done for maximum benefits but requiring certain enabling factors. These **factors could be separately assessed**, as they may be too tenuous for a model (P3). Areas in a spatial modal can also indicate priority areas or areas that are not suitable due to poor carbon storage, high costs, and other model results.

4.3.3 Outputs

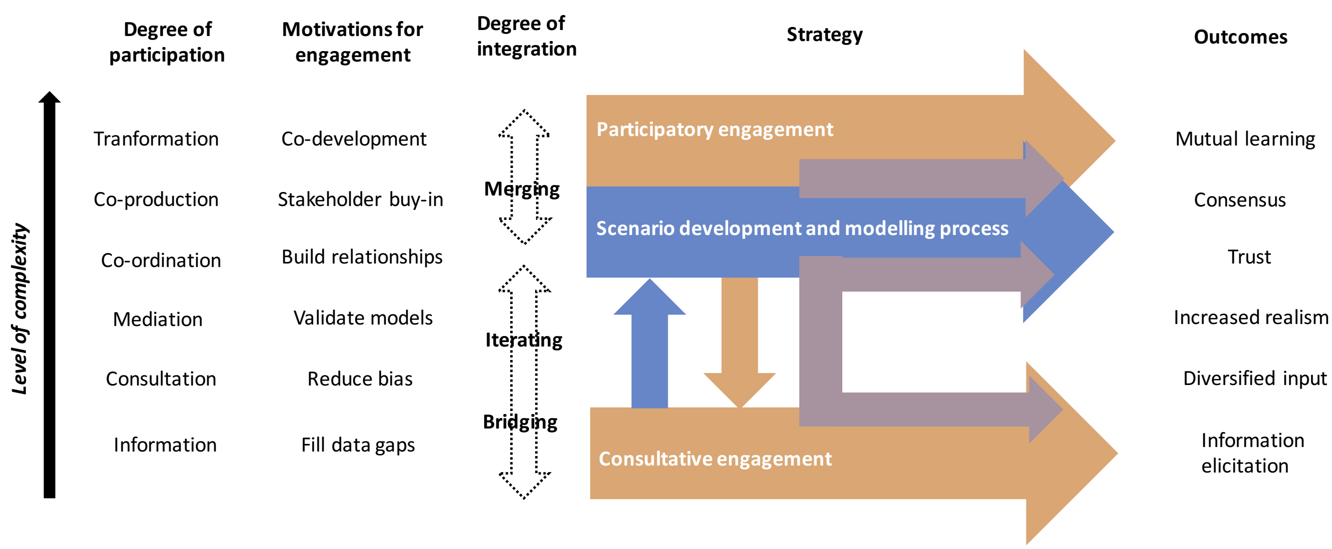
In addition, a number of interviewees also mentioned the **interpretation of results** as an area where there is linkage with the social sciences and topical experts may be called upon for input (P3, P6). It is also important to be clear about the limits of the research and uncertainties.

The **presentation of the model** and results also came up a number of times in interviews. Tools to simplify them and aid in discussions stakeholders and their dissemination and accessibility can be useful (P2, P3, P5, P7).

5. Discussion

Our results confirm our hypothesis that there are different degrees of integration and participation of external actors in the modelling process (**Figure 4**). These interactions are not fixed; the strategy often depends on the project objectives, and may be constrainted by resource limitations. Further, achieving transformational change necessitates that cross-disciplinary research be strengthened and the scope of large-scale models be expanded. Integrated assessment models are no exception (Fuhrman et al., 2019).

Figure 4. Interactions between integration and participation strategies



The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), for example, has 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). In addition, the IAM community has tried and made strides to advance engagement with stakeholders to identify societal considerations, for example with down-scaling the SSPs.

However, research on how to more effectively represent social issues in large-scale models is 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; van den Berg et al., 2019). In part, this may be due to lack of demand from policymakers. As such, we argue for developing a systematic approach instead.

As this research has the aim of contributing to restoration planning for Indonesia, we reflect on the following: are current linkages able to answer the questions we need to to make decisions on nature-based solutions, in particular restoration, on a national level? Specific questions that would need to be answered, as outlined by the International Union for Conservation of Nature's Restoration Opportunities Assessment Methodology (IUCN and WRI, 2014) include:

1. Where is restoration socially, economically and ecologically feasible?
2. What is the total extent of restoration opportunities in the country/region?
3. Which types of restoration are feasible in different parts of the country/region?
4. What are the costs and benefits, including carbon storage and ecosystem services, associated with different restoration strategies?
5. What policy, financial and social incentives exist or are needed to support restoration?
6. Who are the stakeholders with whom we need to engage?
7. What options exist to unlock finance for restoration?

8. How can we scale up restoration?

In their current state, models alone can not answer all these questions, and thus linkage with the social sciences is needed. Based on ths and the results presented in this paper, we propose a possible research agenda, which will direct the second paper in this study:

- Define study scope and scale (in our case, national-level restoration assessment in Indonesia)
- Map the system, for example, by applying Ostroms's institutional analysis and development and/or socio-ecological systems framework to identify key players and action situtations within the study scope
- Develop a typology of actors that reflects any heterogeneity in the study boundaries
- Conduct multicriteria mapping with a sample group of actors and/or experts to identify context-relevant factors and provide ranking or weighting
- Validate the mapping with a broader group of stakeholders via survey methods
- Present and negotiate results of survey with initial group of actors and/or experts

Historically, tools for restoration planning have been focused on spatial and ecological considerations, such as the optimization of land area and vegetation (Jellinek et al., 2014; Newton & Tejedor, 2011; Orsi et al., 2011). These factors, such as the suitability of tree species are also a significant presence in and limitation of the body of current literature (Acosta et al., 2018; Amazonas et al., 2018; Maimunah et al., 2018). While this technical knowledge is essential to restoration planning, restoration scenarios remain limited scope and disconnected from socioeconomic context. At the same time, socio-political factors are crucial to the effectiveness of restoration activities (Budiharta et al., 2016).

A systematic review of restoration scenarios notes that over a third (38%) of the reviewed studies had a goal to restore habitats, and another third (29%) to recover ecosystem services (Acosta et al., 2018). Furthermore, the study indicates that the majority (85%) of restoration scenario studies that consider active restoration (65%) do not account for costs; and very few incorporate participatory approaches (11%). Achieving global and national restoration goals call for more proactive efforts to consider potential problems in ex-ante scenarios, in particular those that may arise during implementation (Ferrier et al., 2016).

Review of individual studies on tools and methods used for restoration planning suggest that the approach depends on the objective and intent of the restoration scenario (Metzger et al., 2017). Restoration scenarios may be exploratory, target-seeking, policy-screening, or retrospective policy evaluations (Ferrier et al., 2016; Metzger et al., 2017). Generally, studies on restoration planning consider: 1) where restoration is needed (e.g. where ecosystems may be vulnerable); 2) where restoration is likely to succeed (e.g. biophysical factors).

A handful of studies look at the cost, e.g. willingness to pay for forest restoration (Mueller et al., 2018) and economic feasibility (Rahman & Mahmud, 2018) in specific case study areas. Studies with an ecological focus included assessments of ecosystem services (Calvo Robledo et al., 2020) and spatial mapping (Fortini & Jacobi, 2018). Multi-criteria decision analysis is often applied in the few studies that use participatory methods (Guo et al., 2020). The level of participation and types of stakeholders engaged range. In studies where stakeholders are more deeply involved, multi-criteria decision analysis may be combined with surveys or workshops (Bohnet et al., 2011; Hein et al., 2017; Loth & Newton, 2018).

In addition, 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. The approach uses ordinal values for biophysical suitability, cultural dependency, community preference and accessibility, and economic dependency to produce a ranking of priority areas. The results of the study indicate that inclusion of social and political factors in assessment of restoration opportunities may result in different priority areas than analysis based on biophysical factors alone. However, the approach does not directly engage stakeholders or community but draws on literature review to develop assumptions on the ecological and socio-economic context when applying the framework.

Research on public participation around river restorations finds that there is a strong case for involving a broader population group, beyond influential stakeholders, in decision making processes, supported by recent expert opinions (Junker et al., 2007; Metzger et al., 2017). Fully participatory modeling approaches remain marginal. A recent study provides a knowledge-based approach to fully engage local communities on the development and application of predictive tools (Meselhe et al., 2020). Community members were involved at the stages of: selection of model domain: boundary conditions; model attributes; and restoration and protection strategies. Similarly, stakeholders co-designed restoration scenarios in another study using the Landscapes Toolkit, spatially-explicit framework that allows for the comparative-static assessment of stakeholder-defined land use and management change scenarios (Bohnet et al., 2011). Stakeholders were consulted via semi-structured interviews, workshops, and discussions of the scenario results. An important benefit for these in-depth, participatory approaches is their ability to engage communities and ensure there is local buy-in.

However, for large-scale (e.g. national) restoration planning, virtual processes for community and stakeholder participation in scenario development may provide sufficient and valid data to improve and complement models and account for socio-political factors. Where studies evaluating restoration options or potential elict stakeholder input, surveys may be used (Loth & Newton, 2018). In a study in the United Kingdom, these were conducted in-person; however, the method could arguably be adapted to an online format. Participant opinions were captured using a likert scale to agree with statements on definitions, areas of suitability, specific scenarios to determine popularity, and potential barriers to implementation and factors limiting feasibility. This was followed by a spatial multi-criteria evaluation and scenario ranking using multi-criteria analysis.

The above illustrates the opportunites and options for the next steps of our study. As such, the second paper will draw on the insights around participation and integration from this first paper to explore how and if a systematic methodology can be developed that adds value to the modelling process for nature-based solutions.

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Annex

Field of enquiry	Detailed questions
	IAM modellers
Background information	What is your current position?
	Years of relevant experience?
	Examples of relevant projects/experiences?
	Which large-scale models/IAMs do you work with?
	Purpose of large-scale models/IAMs? For NbS?
Role of social preferences	What role does social preferences have in NbS?
	How do you rate the significance of considering social preference in NbS compared to other dimensions/aspects in your research?
	How are you (or other work you're familiar with) including social preferences in
Engaging with actors/stakeholders	How do you obtain information about social preferrence (or societal information in general)?
	Is this approach sufficient or sub-optimal? What would be the ideal
	How do you engage with people/stakeholders as source of information?
	How ready are they to provide the information that you require?
	What would be needed to allow you elicit the required information fro stakeholders? Specific methods?
	In your experience, to what extend does the information obtained from stakehodlers get adopted/incorporated into your research work?
Integration into modelling process	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?
	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe
	If not, how are you still incorporating social preference in your use of the model?
	Is this approach sufficient or sub-optimal? What would be the ideal appraoch?

Field of enquiry	Detailed questions
	NbS/topical experts
Background information	What is your current position?
	Years of relevant experience?
	Examples of relevant projects/experiences?
	What kind of models do you usually use in your research activities?
	What are the purpose of the models that you use?
Role of social preferences	Do you work with large-scale models/IAMs? How do they interact with the other models you previously mentioned?
	Purpose of these types of models? For NbS?
	What role does social preferences have in NbS?
Engaging with actors/stakeholders	How do you rate the significance of considering social preference in NbS compared to other dimensions/aspects in your research?
	How are you (or other work you're familiar with) including social preferences in
	How do you obtain information about social preferrence (or societal information in general)?
	Is this approach sufficient or sub-optimal? What would be the ideal
	How do you engage with people/stakeholders as source of information?
	How ready are they to provide the information that you require?
Integration into modelling process	What would be needed to allow you elicit the required information fro stakeholders? Specific methods?
	In your experience, to what extend does the information obtained from stakehodlers get adopted/incorporated into your research work?
	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?
	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe
	If not, how are you still incorporating social preference in your use of the model?
	Is this approach sufficient or sub-optimal? What would be the ideal appraoch?

Field of enquiry	Detailed questions
	Methodology experts
Background information	What is your current position?
	Years of relevant experience?
	Examples of relevant projects/experiences?
	What kind of models do you usually use in your research activities?
	What are the purpose of the models that you use?
Role of social preferences	Do you work with large-scale models/IAMs? How do they interact with the other models you previously mentioned?
	Purpose of large-scale models/IAMs?
	What role does social preferences have in the topics that you have been
Engaging with actors/stakeholders	How do you rate the significance of considering social preference compared to other dimensions/aspects in your research?
	How are you (or other work you're familiar with) including social preferences in
	How do you obtain information about social preferrence (or societal information in general)?
	Is this approach sufficient or sub-optimal? What would be the ideal
	How do you engage with people/stakeholders as source of information?
	How ready are they to provide the information that you require?
Integration into modelling process	What would be needed to allow you elicit the required information fro stakeholders? Specific methods?
	In your experience, to what extend does the information obtained from stakehodlers get adopted/incorporated into your research work?
	Can you describe how the models that you use utilize/assess/consider social preference related issues/information?
	Is social preference a formalized element in your model (i.e. part of equation or parameter)? If yes, please describe
	If not, can social preference still be incorporated in your use of the model?
	Is this approach sufficient or sub-optimal? What would be the ideal appraoch?