# Applying an ethical lens for more responsible modelling practice

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## Abstract

In recent years there has been an increasing emphasis on including humans when modelling socio-environmental systems. However, it is crucial that we remain mindful of the impacts that the decisions made during model development or analysis can have on people or nature as modelling is not an impartial process. Responsible modelling requires us to consider the broader societal implications of our work, therefore, modellers should consider a range of ethical concerns, often found beyond those prescribed through institutionally mandated ethical approval processes. Herein we examine the ethical dimensions of six socio-environmental case studies using the principles of credibility, legitimacy, and salience, encompassing the modelling process from conception to delivery and beyond. We also discuss the results from an interdisciplinary workshop held with experienced modellers to co-produce a list of ethical dimensions that modellers would ideally engage with when conducting a modelling project. Based on our findings, we have developed a set of recommendations to: i) support modellers in ensuring their modelling practice is underpinned by ethical reflection, ii) guide end-users of model outputs when selecting and repurposing those outputs, and iii) identify means by which institutions can support responsible modelling practices. Engaging with ethical dimensions in the process of modelling is critical for building trust with stakeholders, therefore enhancing the credibility, legitimacy, and salience of the models and research.

## Keywords

ethics; responsible innovation; socio-environmental models; sustainability; model development

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# 1. Introduction

An oft-repeated mantra in modelling is that "all models are wrong [but some are useful]" (attributed to Box, 1976), which is meant to remind all involved that models are an incomplete representation of reality. It is also true that modellers (and model users) are only human, which can mean that for a diversity of reasons (e.g., well-intentioned focused enthusiasm, not being mindful, work pressure, or other poor practices, etc.) the development or use of models may fail to live up to the ideal. While never a desirable position, it is even more troubling now as an increasing number of decisions, affecting many aspects of our lives, are based upon models – from electricity supply to traffic flow, medical interventions, infrastructure investments, and regional to national scale planning and insurance assessments, to name just a few. This has put modellers at the sharp end of the potential to influence lives and livelihoods. Simultaneously there is growing pressure on modellers to produce skilful, well performing models, often under the dual mandate of being timely and expenditure conscious. At the user end, models may be treated as gospel, where instead they should be seen as a tool that can help to support decision-making. There are growing expectations for responsible modelling practice (e.g., Ormerod & Ulrich, 2013; Saltelli et al., 2020; Saltelli & Di Fiore, 2023). We believe this is a critical time for the modelling community to advance responsible modelling practice by considering and navigating ethical dimensions of their work. Given that many modellers are not trained in ethics, we suggest that those who design, develop, and communicate models, alongside model end-users, would benefit from tools to assist with responsible modelling.

With this aim, perhaps the first idea to grapple with is the western science concept of objectivity. Just as no model can replicate the complexities of the real world, no individual can know everything. People make decisions with incomplete knowledge, based on mental models, informed by accumulated knowledge and intrinsic and learned ways of thinking (Russell, 2010). Our mental models are influenced by many factors, for example, personality, neurotype, capacity for complexity, or life experiences. Through culture and education (our academic lineage), the perspectives of prior generations have been embedded into the act of knowledge generation to shape our current ways of thinking, worldviews, and types of data collected (e.g., Jones et al., 2011; Mercer & Simpson, 2023; Russell, 2010). For example, the structure of complex systems can be represented quite differently in the mental models of individual system experts (Levy et al., 2018; Schaffernicht & Groesser, 2024; van den Broek et al., 2023). This diversity of perspective means modellers are unavoidably partial in making the many decisions involved in developing models – such as system boundary, variables, and data – with studies demonstrating how differences in models and decisions by modellers lead to differing model predictions for the same question (Holländer et al., 2014), and how different research teams can draw highly variable conclusions from the same set of data (Gould et al., 2025). The plurality of ways to model a system and the consequent variability in possible impacts on different people at different scales highlights the importance of careful thinking about the ethical dimensions of the modelling process, i.e., the awareness by the modeller that modelling cannot be separated from its social and political uses and impacts, even in the case of biophysical and socio-environmental models (Picavet, 2009). Alongside this is a plurality of knowledge systems, where people may understand the world in very different ways. The representation of a system via a model may not fit with the understanding of all people concerned, with justice implications for those whose knowledge is marginalised (Hird et al., 2023; Urzedo & Robinson, 2023; Zimm et al., 2024). Responsible modelling practice requires acknowledging and deliberatively navigating positionality, equity, and justice across scales.

Considering the potential for harm in science and engineering research, many disciplines and professions have a strong requirement for ethics; however, formal ethics approvals for scientific research follow the medical model of informed consent (Shuster, 1997). This framing focuses on potential harm to research subjects that might directly arise from their involvement in the study, however largely fails to consider broader ethical considerations such as how the study might contribute to biased knowledge (Richards et al., 2024), or paradigm generation that causes harm to current or future populations (McLaren, 2018). Many modelling projects do not directly involve collection of data from people or animals, and so those involved may not be explicitly prompted to consider ethical issues. Nevertheless, modelling practice can still affect society, leaving individuals vulnerable to model results. For example, IPCC scenario modelling includes low emissions pathways that are heavily reliant on mitigation strategies that – if they were feasible at the scale assumed in the model – would significantly impact land use and cause displacement of people (Beck & Mahony, 2017; Buck, 2016; Lenzi et al., 2018). Zimm et al. (2024) refer to this as transitional justice, where unjust policies (e.g., regressive taxes, non-consultative land acquisition, unsupported mine closures), are used to support just outcomes (e.g., net-zero carbon emissions). This modelling approach has been used to justify delaying action and policy on climate change in many high-income countries, despite the technology not being viable at scale. The consequences of this lack of

action will disproportionately be experienced by lower-income countries. By examining the ethical dimensions of modelling, the potential outcomes that may exacerbate vulnerability can be made more apparent in the model outputs.

Applying the principles of 'credibility, legitimacy, and salience' (Cash et al., 2003) ('CLS' hereafter) can support researchers to reflect on ethical considerations of modelling. In this sense, models should use technically adequate knowledge to be credible, to address the concerns and needs of models' users (salient), while respectfully considering different worldviews and knowledge (legitimate). Thinking through for who, why, and how each of these critical aspects of any research endeavour could be met provides an opportunity to consider both positive or negative implications of models for different stakeholders and their capacity to influence associated decision making. The challenge in navigating CLS increases with the number of stakeholders involved (Kunseler et al., 2015). Therefore, integrating multiple stakeholders' knowledge is a skillset that some modellers interested in co-producing knowledge should develop (Robinson et al., 2023). The CLS principles have been used to support model uptake by policy actors (van Voorn et al., 2016) and as part of model evaluation criteria (Hamilton et al., 2019). Using an ethical lens informed by the CLS principles can help with the ongoing challenge for modellers to understand the socio-political implications of their work and situate it in a science-policy context. Such a lens will help to maintain the credibility of scientific inputs, while being open to how other knowledge and expertise can inform the model and provide alternative framings to the assessment. Beyond the CLS framing, practical tools would help to support reflexivity and guide modellers (and others) in navigating the ethical considerations and tensions relevant to their modelling choices.

This paper aims to provide practical support for instilling ethical considerations into modelling socio-environmental systems using reflexive processes. Specifically, this work aims to: i) support modellers in the ongoing learning of embedding ethical reflection as part of their modelling practice; ii) guide end-users of model outputs when selecting and repurposing those outputs; and iii) encourage greater institutional support for embedding responsible modelling practices. Our motivation for this paper is to demonstrate that modellers must consider the ethical implications of their work during all stages and that there may be more ethical dimensions to their work than they might initially expect. Many of the author team are modellers themselves and contend with ethical issues in their own work. Section 3.1 of this paper contains reflections by individual authors on their experiences.

# 2. Methods

Our approach to developing a practical guide for identifying and addressing ethical considerations in socio-environmental systems modelling is based on qualitative analysis and reflexivity. Qualitative analysis is a form of inquiry into the meanings people place onto the phenomena they experience in the world (Denzin & Lincoln, 2018). Our practice of reflexivity involves reflecting on the methods we use, the assumptions upon which we base our work, recognising the limitations of our knowledge, and being aware that our framings of research problems may be only one of many viable alternatives (Stilgoe et al., 2013).

We used two approaches for these reflections and analyses. The first was to critically reflect on case studies of different modelling projects the authors have engaged with previously (which we have generalised for the purpose of this publication) to elicit ethical insights, using CLS principles. The second approach was via participant action research during a workshop, where researchers guided participants through a two-stage ethical reflection after which the group collectively devised a set of ethical considerations for modellers. In both approaches, we performed a thematic analysis of the data to identify common themes.

## 2.1 Author positionality

One important method for researchers to perform reflections is to consider and acknowledge their positionality as a researcher (Beck et al., 2021). The author team acknowledge a bias in their expertise towards systems modelling as they predominantly work in sustainability science applications, though the team includes expertise across biophysical and social sciences, and quantitative and qualitative research methods. We currently work in transdisciplinary spaces and actively navigate principles of inclusive knowledge co-production which consider power dynamics and justice implications. We are majority female, early- to mid-career researchers working at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's National Science Agency, which situates our research into a particular techno-sustainability paradigm of applied research in the Australian

context. We have diverse life histories, personal purposes, heritage, and nationalities, including one with Indigenous Australian ancestry.

## 2.2 Credibility, legitimacy and salience

Although models can have different purposes, they are ultimately used to inform decision-making processes. For modellers, a persistent challenge lies in comprehending the political implications of their work and situating it within a decision-making context. This involves a delicate balance: maintaining the credibility of the scientific inputs while being receptive to how other knowledge and expertise can enrich the model and offer alternative perspectives to the assessment.

A non-exhaustive literature review on CLS principles was conducted to identify the political and ethical implications of modelling. The review helped to identify a preliminary list of criteria to consider at different steps in different types of projects (Hamilton et al., 2019; Kunseler et al., 2015; van Voorn et al., 2016). With these criteria, and following van Kerkhoff & Pilbeam's (2017) knowledge governance framework, we identified a list of questions to help researchers self-assess their modelling approaches (Table 1). These questions were validated before the workshop through an informal interview.

### 2.2.1. Case study reflection

Six authors on this manuscript provided a reflection on a modelling research project they had been involved with or had experience with (Table 2). These case studies included biogeochemical carbon modelling, socioecological scenario modelling, integrated systems modelling of climate change and health risks, ecological economics modelling of food systems, qualitative conceptual modelling of Indigenous harvesting practices, and one hypothetical case study of biophysical process modelling, informed by the modeller's experience. Each case study described the modelling project and broadly attempted to examine it, framed by questions regarding credibility, legitimacy, and salience (Table 1) (Cash et al., 2003). The authors identified examples for each of credibility, legitimacy, and salience, and then commonalities were synthesised from these examples. In general, credibility explores whether stakeholders can trust the model and its outputs; legitimacy is closely tied to justice, fairness, and bias; and salience focuses more on the end result – is it useful for the end user, and whether the is model relevant to the questions being asked of it (Hamilton et al., 2019). The case study reflections were then examined through the emergent categories of ethical dimensions derived from the workshop (see section 2.3) to explore the alignment of the reflections with the dimensions, and the observations synthesised into a table for analysis. This reflection exercise was a way to support our own reflexive practice as modellers, using the CLS principles as a framework for identification of ethical issues that we may not be practised in considering.

## 2.3 Participant action research workshop

In October 2023, the project team designed and delivered a three-hour online workshop on 'Ethics in modelling, data and AI' for a group of scientific modelling professionals at CSIRO, Australia. There were 20 participants in the workshop, with expertise in bioinformatics, digital architecture, energy systems, ecosystem and network modelling, cybersecurity, software and legal systems, social media, and human-computer interaction (Supplementary Material A). This workshop received human ethics approval from CSIRO's Social and Interdisciplinary Science Human Research Ethics Committee in line with the guidelines specified in the (Australian) National Statement on Ethical Conduct in Human Research (ethics clearance No. 171/23).

The aim of the workshop was to create a space for the participants to explore ethical considerations of models and modelling projects, and to collaboratively develop a practical list of ethical considerations that modellers could engage with when designing, developing, and delivering a modelling project. The workshop provided some prompts for different ways of thinking about ethical implications of models, data, and AI, creating space for participants to learn from each other's different expertise and experience, while acknowledging the value of the diversity of perspectives despite potentially differing levels of exposure to these considerations previously (Supplementary Material B).

The workshop was structured to provide participants ample opportunity to engage with concepts and each other. Accordingly, structured group (small or large) discussions were interspersed with short presentations that provided additional prompts for thought. Initial group discussions focused on a hypothetical socio-environmental case study brief (Supplementary Material B) and later extended to ethical issues encountered more broadly amongst the group.

**Table 1:** Themes and questions used to prompt reflection on ethical considerations in model case studies. The second column explains the rationale and more detailed inquiry for each (adapted from Hamilton et al., 2019; van Kerkhoff & Pilbeam, 2017; van Voorn et al., 2016).

| Theme | Rationale and suggested questions for self-evaluation |
|---|---|
| Aim of the model | Consider the purpose for creating the model – what are the potential ethical implications, and for who, including beneficiaries or people negatively affected by the findings or implementation of them?<br>If and how policy and research motivations are translated into research questions? |
| Knowledge preferences | Modellers should make explicit the standards used to manage evidence-based information, and also consider how their own positionality shapes problem framing or modelling choices.<br>What motivations or assumptions exist for the use of knowledge when creating a model?<br>Whose values and assumptions are informing the model?<br>How relevant is the output to decision making?<br>Who are the end users? |
| Role of participation in supporting credibility and what strategies exist to communicate and translate across scientific/non-scientific communities | Consider how/if the participation of stakeholders and the use of their knowledge and values are encouraged in creating the model. Also, consider how the results are communicated to stakeholders beyond decision-makers.<br>Are there other forms of knowledge not currently in use that can inform or validate the model? If so, who holds that knowledge?<br>How can stakeholders be affected by the outputs of the assessment (winners/losers; behaviour change)? |
| Expertise | Modellers should examine existing social and political issues shaping institutional preferences to define expertise.<br>Is expert status held personally or institutionally?<br>Whose voices and expertise are used to inform the model?<br>Are there any criteria for expertise stated formally in decision making processes, or applied informally?<br>What are the expectations from stakeholders in how their knowledge/expertise is used? |
| Effectiveness – demonstrating benefits or outcomes to the wider public | Consider how the modeller includes feedback from stakeholders. Modellers should be aware of potential data manipulation that might affect the benefits or outcomes to the public.<br>How are social and environmental responsibility issues considered when communicating/sharing outputs with the broader community and decision-makers?<br>Are any potential conflicts recognised?<br>Whose interests are included or excluded?<br>Are there criteria to involve stakeholders at different levels of the process (inputs, feedback, delivery)?<br>Are there any future risks assessed? |

**Table 2:** Modelling case study descriptions.

| Case study number | Topic/ sustainability problem | Discipline | Scope/scale | Location | Modelling type | Outputs |
|---|---|---|---|---|---|---|
| 1 | Drivers of malaria risk under climate change | Climate change and health | Regional | East Africa | Participatory socio-ecological systems model (stakeholder input) | Integrated risk framework and model; Adaptation options and strategies for decision-making |
| 2 | Local scale pathways to sustainable futures | Sustainability science | Local | Small regional town in Australia | Participatory systems model (co-produced) | Pathways, strategic plan |
| 3 | Food packaging impacts | Ecological economics | Global | Global food systems | Causal loop diagrams (stakeholder input) | Causal loop diagrams and a stock and flow model |
| 4 | Hypothetical case study based on modeller experiences | Integration science | Non-specific, based on experience with different scopes and scales | Non-specific, based on experience in various locations in Australia | Diverse modelling types | Scientific understanding, insights, modelling methods |
| 5 | General examination of modelling biogeochemical cycles | Soil science | Multi-scale: global to soil | Australia | Biophysical carbon models | Carbon emission data |
| 6 | Drivers of customary harvesting | Human-environment geography | Local/regional | A remote First Nations community in Australia | Qualitative conceptual model | 'System' understanding (drivers of change, decision making, and interconnections) |

Workshop participants were taken through the following activities (see Supplementary Material B for details):

1) Warm-up: Initial brainstorming to identify ethical issues from a hypothetical case study in small groups of 4-6;
2) Facilitator presentation on ethics and modelling;
3) Continuation of the small group hypothetical case study activity, but with inclusion of a stakeholder mapping exercise using an interest-influence matrix;
4) Larger group reflection and discussion;
5) Facilitator presentation on AI and ethics;
6) Collectively generating a practical list of ethical issues in plenary.

These activities also included significant time for discussion and reflection by participants.

We used the online platform Miro (Miro, 2023) to collaborate with participants and record responses and observations during the online workshop. The researchers also used Miro after the workshop to summarise the data and perform thematic analysis.

#### 2.3.1. Thematic analysis

The thematic analysis of ethical considerations generated in the workshop was conducted independently by four members of the co-author team, each using their own process and perspectives with an inductive approach (MacFarlane & O'Reilly-de Brún, 2012). The themes identified from these thematic analyses were then synthesised into a set of 11 ethical dimensions. See Supplementary Material C for further details on these methods. While the dimensions were developed from the emergent themes in the workshop, we deliberated on each of them to develop descriptions and example questions, similar to the CLS questions in Table 1.

## 3. Results

### 3.1 Credibility, legitimacy, and salience analysis of case studies

Here we synthesise reflections of six diverse modelling case studies drawn from different sustainability issues and disciplines (Table 2). Each case study was examined following the prompt questions from Table 1. More details on each case study are provided in Supplementary Material E. First we summarise the aspects of the reflections which directly related to the CLS principles, and then examine other key points raised with respect to responsible modelling practice.

With respect to credibility, the reflections focused on inclusion of relevant knowledge in the model: the omission of agency from the model limited its usefulness (i.e., who is responsible for systemic change?); a 'fear' of getting something wrong; reliance on 'best educated guess' input data. Elements of justice also featured, with the prioritisation of knowledge from western researchers rather than Indigenous knowledge holders; and the need for culturally appropriate knowledge holders to be identified by a local authority instead of relying on modeller assumptions. Regarding model legitimacy, authors questioned whether co-production or participatory processes occurred: without group model building, emergent solutions were not able to be identified; a multi-stage model development process created challenges with representing stakeholder perspectives; whose needs were being met with the development of the model when key stakeholders supplied knowledge but were not provided with results of the modelling. One example noted that a lack of available data for some countries reinforced existing inequities in data collection capabilities. Respect for stakeholders and their knowledge was noted several times, from needing to understand cultural complexity, to respect for sensitive information and flexibility in model design. Regarding salience, the reflections identified that communication of project results was important to inform societal change, that project outputs other than modelling results may be more valued by some stakeholders, and caution with respect to universalisation of modelling, i.e., that the model or findings may not be relevant for different contexts and scales.

The case study reflections indicate that the ethical aspects of models are often not addressed across all stages of modelling. For example, reflections mention how limited stakeholder participation affected the usability of information, which had implications for how the problem is framed and what information is used in the model (case study 1). Also highlighted was the way that socio-political structures shape preferences for certain types

of knowledge. The results indicate that institutions often don't question ethical aspects of models based on technical knowledge (e.g., carbon models in case study 5) as these are seen as inherently credible. "Projectification" was another theme explored in the reflections; where models are seen as an output, and institutional barriers make it difficult to repurpose or update the models. This includes a lack of suitable support of 'legacy' models, meaning that use of models does not continue beyond the project (wasting time, effort, and resources that were expended in developing them), or if their use continues, it may be inappropriate to the new context. This theme of projectification was also reflected in the limited time and resources available to engage in complex/sensitive contexts (case studies 2, 6), or to validate the results with different stakeholders (case studies 1, 3).

Modellers may need to engage with sensitive issues (e.g., poverty, inequality), and the ethical aspects of such issues may often not be properly addressed by modellers, or they receive little institutional guidance on how to address them when engaging in participatory modelling (case study 2). Reflecting on CLS principles helped modellers to evaluate the overall outcomes and their own choices when modelling a system. It also raised questions regarding individual and institutional reflexivity, and the importance of being able to revisit and correct models as they gained a better understanding of the problem and the system being modelled (case study 4).

## 3.2 Participant action research workshop

Workshop participants proposed ethical considerations of both the individual researcher's responsibilities within a project and the assumptions embedded within the data and the model, spanning a variety of themes and topics that were presented as both statements and questions. These emergent themes categorise ethical considerations present in different aspects of modelling projects and also explore ways to improve support for modellers navigating ethical considerations. It is worth noting that some (or even many) ethical issues fit into more than one category, illustrating the multiple dimensions of those ethical issues. We hereafter refer to these themes as 'ethical dimensions' that can help guide examination of possible ethical issues in modelling projects and workplaces. These ethical dimensions are presented in Table 3, and examples of ethical issues drawn from the co-production workshop are presented for each dimension in the Supplementary Material D.

## 3.3 Alignment between ethical dimensions and case study reflection

The case study reflections were analysed to identify alignment with the ethical dimensions identified in section 3.2 (Table SI1). This alignment was not a re-examination of the case studies with the ethical dimensions, but of the reflections themselves. The frequency analysis of how many of the dimensions were observed in the reflections is presented in Figure 1. This frequency analysis only yields surface-level insights but does suggest that the list developed from the workshop broadly covers the range of ethical considerations that modellers might expect to face, although the two dimensions which were least engaged with in the reflections are noteworthy (9 and 10, Figure 1). *Model repurposing* generally exists outside the scope of a modelling project and modellers may not even be aware their work is being reused. Furthermore, it is not surprising with the nature of these project-based reflections that only one author considered *Fostering responsible modelling practice and culture for modellers* as this is a more holistic dimension that is more about workplace and professional culture than it is about specific modelling projects. We will explore these ideas further in the Discussion.

**Table 3:** Synthesis of ethical dimensions identified from the ethics in modelling workshop, and example questions that modellers could consider to examine each dimension. The dimensions were developed from emergent themes from workshop discussion, and can help guide reflection of modelling projects to identify ethical issues that may be relevant.

| Ethical dimensions | Description | Example questions to consider |
|---|---|---|
| 1. Justice in problem framing | How a problem is framed determines the questions being asked, the approach taken, and the resultant findings; therefore, different problem framings can potentially have different flow-on consequences for diverse stakeholders.<br>This dimension encourages researchers to consider the justice implications of the modelling project, and to acknowledge their positionality when framing the problem. (see section **Error! Reference source not found.**) | What are the potential differential impacts of model development and model output?<br>What is the positionality of the project team and how might that influence the process?<br>Does the problem framing the consider potential biases and power dynamics amongst diverse stakeholders?<br>Does the model have capacity to accommodate plural worldviews (e.g., through scenarios)? |
| 2. Project planning: justice in design and outcomes. | Processes for responsible modelling should be embedded into project planning from the outset. Proactively design approaches for managing ethical issues that are likely to arise at different stages of a project.<br>This dimension involves developing a project plan that embeds processes for considering, monitoring, and managing ethical dimensions across all stages of the modelling project, with opportunities for reflection throughout. | Who is affected by activities at different stages of the modelling, and by decisions made based on model results, and how are they affected?<br>How will the model development and outputs manage differences in values, priorities, and perspectives amongst knowledge holders?<br>How can trade-offs be analysed, understood, and communicated?<br>Does the project team have sufficient capacity and resources to manage ethical risks or issues that may arise throughout the project lifecycle? |
| 3. Ethical engagement | Researchers have ethical responsibilities towards stakeholders and to themselves, therefore it is essential that all interactions and collaborations with stakeholders are held to the highest ethical standards.<br>This dimension includes considering appropriate means of engagement, ensuring adequate resourcing, maintaining effective communication, and managing expectations. | How can researchers conduct ethical interactions with all stakeholders?<br>Are cultural considerations taken into account when interacting and designing engagements?<br>Are there processes to navigate inequities and power dynamics between stakeholders?<br>Does planning for engagements incorporate the needs of all stakeholders (e.g., timing, resourcing, accessibility, etc)? |
| 4. Model development | Decisions made during model development influence the scope of findings and their implications for various groups. This includes choosing the type of model, whether variables or processes are suitable or appropriate, determining the resolution and spatial scales, and deciding how to represent different perspectives in the model.<br>This dimension acknowledges and addresses that embedded assumptions, knowledge gaps, and dominant interests or worldviews can influence outputs and credibility of the model. | How have ethical considerations been recognised in developing the model?<br>Have assumptions been scrutinised and documented?<br>Is the model boundary and scope appropriate? Whose knowledge informed those decisions?<br>How will model choices influence the type of knowledge generated, and how might that impact diverse groups at different scales? |

(*Table continued on next page*)

Table 3 *(continued)*

| Ethical dimensions | Description | Example questions to consider |
|---|---|---|
| 5. Justice in information and resources | Models can have ethical assumptions embedded within the data and the model, particularly where ethical issues and decisions that aren't dealt with early on compound to create *ethical debt* and *path dependency*.<br>This dimension recognises the specificity and uncertainty of the data, the purpose for which data and resources were originally collected/created, and whether reuse is appropriate. For example, using data as a proxy for the true variable of interest might bias findings and have flow-on consequences. | What are the origins and previous applications of the data and sub-models used in the project?<br>How can the knowledge which is used to create models be incorporated while being respectful of its provenance?<br>Who has knowledge of the system and can give balanced advice on potential ethical tensions?<br>Could the model outputs preserve ethical debt and path dependency, e.g., negative impacts on marginalised people, or entrenching deleterious outcomes? |
| 6. Characterise uncertainties and limitations | Researchers bear ethical responsibilities in project reporting that includes transparent confrontation and clarification of the uncertainties, assumptions, and biases embedded in the modelling project.<br>This dimension involves conducting sensitivity and uncertainty analyses (including structural, parameter, and prediction uncertainty arising from the choice of methods or scenarios). | How has the model been tested and verified?<br>Is there evidence that the model works? What patterns can the model reproduce? Under what conditions are the model predictions valid?<br>How do sensitivity analyses affect the degree of confidence in different findings?<br>Has the uncertainty been comprehensively examined, and can any uncertainties be reduced? |
| 7. Evaluation of outcomes | Evaluating project outcomes is a critical ethical stage for researchers. This includes interpreting the findings in the context of uncertainties and sensitivity analyses and assessing the strength of confidence in various outputs.<br>This dimension invites researchers to consider the implications of their findings for diverse groups and environments, including differential impacts and trade-offs at different scales, and determine whether further analysis is required to ensure ethical delivery and communication of findings. | Do the model results/outputs equitably support the needs of diverse groups and environments?<br>Could findings with high uncertainty disproportionately disadvantage groups of people?<br>Have the model results been evaluated with benefits and trade-offs assessed?<br>Could additional analyses support decision-makers in using outputs for more equitable outcomes? |
| 8. Clear communication | Responsible communication of model findings and outputs is a key ethical consideration. This includes discussing uncertainties, trade-offs, assumptions, limitations, and what uncertainty means in the model results context.<br>This dimension encourages researchers to develop a communication plan that considers the needs of different audiences, for clear and transparent communication about what constitutes appropriate or inappropriate conclusions, and the potential future applications of the model. | How can results be communicated to support responsible use of findings in decision-making?<br>Are model results comprehensible to all stakeholders? e.g., presenting graphical outputs vs telling stories.<br>If there are negative or ethically questionable outcomes, have these been communicated clearly?<br>How can trade-offs and uncertainties be communicated to support understanding and appropriate interpretation and use of findings? |

(*Table continued on next page*)

Table 3 *(continued)*

| Ethical dimensions | Description | Example questions to consider |
|---|---|---|
| 9. Model repurposing | The potential future applications of the model present important ethical considerations that should be addressed in the context and appropriateness of either repurposing a model in your own work or others repurposing a model you developed.<br>This dimension considers where responsibility lies when models may be used for unintended purposes, including the possibility of *ethical debt* (i.e. failure to recognise new ethical issues when an existing model is used in a new context). | Has a model designed for a different purpose been reused?<br>Has the provenance of the prior work been examined?<br>Is the reuse appropriate, e.g., are there specific cultural or relational aspects to the model that could be unsuitable in a different context?<br>Could there be biases present in the reused model which would affect the new context? |
| 10. Fostering responsible modelling practice and culture for modellers | Researchers have an ethical responsibility to uphold professional and personal principles and build self-awareness through examination of their biases and positionality.<br>This dimension invites modellers to engage with building their individual and community capacity to identify and navigate ethical dimensions, and contribute to raising expectations within the profession regarding the ethical dimensions of modelling work. For example, by creating a community of practice centred around ethical modelling both within and outside organisations as a safe space to discuss and seek advice on ethical issues. | Are there ethical implications that modellers may not have considered in their work, and has this been raised in professional contexts before?<br>Can this be discussed with colleagues, mentors, superiors?<br>How could you contribute to developing a culture of openness and curiosity which enables exploration of concepts in professional development beyond what might be considered as 'standard'? |
| 11. Organisational positionality and responsibilities | Research organisations have ethical responsibilities to their researchers to foster psychosocial safety. Ethical issues can be numerous, diverse, and challenging to address, which can be overwhelming and disheartening for individual modellers. This dimension considers the role that organisations play to provide guidance, resources, and support to help modellers navigate ethical dimensions of their work. Clarity is required regarding distribution of responsibility between the modeller/project team and the organisation. Any issues that cannot be resolved should be managed according to agreed procedures. | What is the distinction between personal responsibility and organisational responsibility when it comes to ethical questions in modelling?<br>Do organisations recognise there are many ethical considerations beyond those requiring ethics committee approval?<br>How can organisations support modellers to develop their own professional ethical practices?<br>Is it clear who bears responsibility for different ethical aspects in a project? |

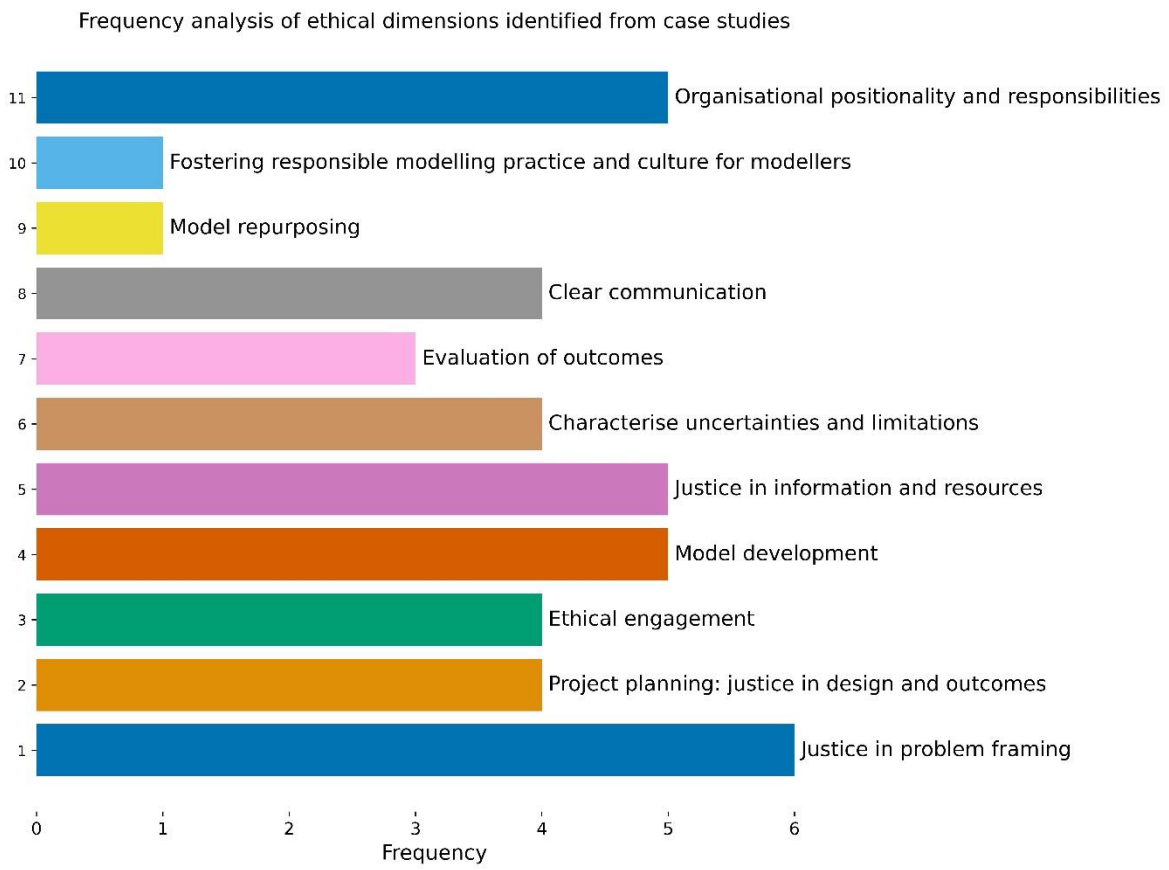


**Figure 1**: Frequency analysis of ethical dimensions that were expressed within case study reflections (n=6).

# 4. Discussion

In this work we have endeavoured to investigate a breadth of potential ethical issues that may arise through engaging with modelling, and in doing so have developed two tools for supporting modeller reflexivity. This was done through self-reflection of our own modelling work using both hypothetical and real-world case studies, using the CLS principles to prompt the reflection, and through discussion and discovery in a workshop setting with modelling professionals. To aid uptake of these reflexive tools, here we discuss the benefits, limitations and application of the CLS questions (Table 1) and the ethical dimensions (Table 3). Following that, we consider justice implications in modelling, and ways to foster responsible modelling practice and culture. Finally, we present a set of practical suggestions for modellers, users of model outputs, and institutions.

## 4.1 Frameworks for modeller reflexivity

We have provided two different approaches for self-reflection in this paper – the CLS questions, and the list of ethical dimensions. Both have value, and we believe it is helpful to examine how the ethical issues identified might differ between the two framings. In general, the ethical dimensions are more specific to modelling than the CLS framing. They provide a nuanced consideration of uncertainty and biases, the impact of those on model outputs, and how they are communicated along with findings. They can also prompt more detailed consideration of the impact of model choices on outputs/findings, and how those choices could influence decision-making with differential impacts on different populations in the future. The dimensions also suggest considering the of role of individuals, collectives, and organisations in fostering and supporting responsible modelling practice. The CLS principles are less specific but can examine the modelling process from an external perspective – there is an implication in credibility, legitimacy, and saliency that these are judgements that will be rendered from without, that “for whom” can be appended to each principle. These perspectives should be considered when deciding on which reflexivity framework to use.

The CLS principles prompt reflection on the model purpose and context; knowledge preferences and expertise; inclusion and participation; and effectiveness in demonstrating outcomes. While the framing aims to encourage reflection on the perceived credibility, legitimacy, and salience of the model (external judgement), the questions posed in Table 1 encouraged reflection on what and whose knowledge was perceived as credible, legitimate and salient to the model (internal, judgement of modellers). Our team found it useful to trace how the answers to the questions might relate to the credibility, legitimacy and salience of the models.

Another framework is the five principles for best practice in modelling proposed by Saltelli et al., (2020). They focus mainly on the process of modelling, focusing on assumptions, complexity, framing, quantification and uncertainty, and unknowns, which were also identified in our work (Table 3). We believe the divergences between Saltelli et al., (2020) and our ethical dimensions stem from the concepts of justice and stakeholder interaction/collaboration. Comparing their work with ours highlights that there are two main categories of ethical concerns: endogenous, which are elements that are intrinsic to the model and modelling process (many of which Saltelli and colleagues identified); and exogenous, which are elements external to the model and can be either pre- or post-model development, or related to the philosophy of modelling. When these two categories are identified, it becomes clearer why modellers gravitate toward identifying some ethical issues over others in a post-hoc self-reflection, while a general discussion which is divorced from particular projects lends itself to recognising more abstract issues. As modellers, these categories are worth bearing in mind during the life of a modelling project, and devoting extra attention to the exogenous ethical considerations that may be overlooked should be considered. However, we cannot definitively categorise the ethical considerations as being either endogenous or exogenous as it can be context-dependent, as discussed in the next sections.

## 4.2 Exploring case study reflections

The CLS principles allow for deep examination of many different ethical issues in modelling practice. Several examples of ethical issues explored in the case studies involved socioecological or integrated models (case studies 1-4 and 6), however, it is important to recognise that these ethical dimensions are also present in models that are 'purely' biophysical. Humans create the models and their assumptions about the system influence decisions about what is included in the model. As case study 5 highlights, unscrupulous use of biophysical model outputs may still result in disadvantage to a person or community. Case study 4 identifies the idea of equifinality, where multiple valid models may represent the same biophysical systems (Beven, 2006), which is linked to the example discussed in the introduction where hundreds of researchers created different, heterogeneous models from the same datasets (Gould et al., 2025). These issues fall into the category of exogenous ethical considerations, whether in a planning sense (deciding which is the best or most appropriate model(s) to use), or from a philosophical sense (knowing which model(s) to use and why that decision was made).

Another issue noted in more than one case study (case studies 2, 3 and 4) is the 'projectification' of many modelling projects, where a model is created as part of a project, usually tied to time-limited funding. Once the project is complete, barriers are raised which limit opportunities to revisit the work, make corrections, communicate and validate the findings with stakeholders, and/or update the model in light of new knowledge. Ethical implications arise if such models continue to be used after their initial development, without considering changed contexts. Even models that are co-produced with knowledge-holders may lose currency with changing circumstances (case study 2), or the model may simply not be a priority for them (case study 6). Alternatively, if a modeller is hired for a fixed-term contract which expires after the model has been completed, but before delivery of the project is complete, where does responsibility for delivery lie? This is another exogenous problem, where the responsibility should lie with the contracting organisation, but can also be related to an ethical modelling culture that can deprive modellers of agency, minimising the ethical and political implications of their work. Beyond who is responsible, another argument here is about barriers to communicate, validate, or disseminate outputs, and how it affects decision making. In this case we might need to consider whether the model is the boundary object for collaboration and decision-making; the credibility of the output – and credible for whom? – (e.g., case studies 3 and 5); or whether the model development is part of a deliberate process of engaging, listening, and learning with stakeholders/decision makers, with the modeller immersed in the process (e.g., case studies 1, 2, and 7). Therefore, institutions should pay more attention to how and why they engage in modelling and consider how to involve modellers in a way that produces ethical, actionable knowledge. For example, institutions can consider how experts are identified, if and how modelling processes are reinforcing power imbalances, or issues of transparency and accountability of model outputs (van Kerkhoff & Pilbeam, 2017; Wagner et al., 2024).

Case study 5 presents a contrast to many of the other case studies, in that it examines models of biogeochemical cycles without an explicit social aspect. One point observed in the reflection is that institutions often don't question ethical aspects of models based on technical knowledge as these are seen as inherently credible. Potential implications of this are that a narrow focus on technical knowledge to the exclusion of other knowledge and expertise might have resulted in models perceived as inherently credible by many decision makers, but which could lead to policies narrowly tailored to the outputs of the models to the exclusion of other possible solutions (e.g., policies in Australia that are focused on soil carbon but do not address structural problems of climate change, or policies that fail to have impact at the local level due to poor communication). In other words, the models may encourage policies focused on tweaking parameter values within the system, rather than more effective leverage points for system transformation (e.g., Abson et al., 2017; Meadows, 1999).

## 4.3 Exploring ethical dimensions

The ethical dimensions that emerged from our analysis (Table 3) highlighted factors that are considered in suggested CLS frameworks with respect to environmental modelling (Hamilton et al. 2019, van Voorn et al. 2016). For example, our results identified ethical issues associated with model development that may reduce the credibility of a modelling project if not considered. A strong theme discussed in the workshop was uncertainty both within the model and the implications for model outputs. Characterising uncertainty and limitations can build legitimacy by confronting the assumptions and biases made in the modelling project. Similarly, evaluating the outcomes of a modelling project can increase salience by considering impacts at relevant scales for end users (decision-makers and diverse groups of people) given the uncertainties and limitations. A consideration we have tried to prompt through the example questions in Table 3 is how implicit bias could be introduced through being unaware of the provenance or previous use of data or models.

Clear communication can help address these issues before or as they arise. For instance, being transparent with what is included and excluded from the model to increase credibility – one author notes that most modellers are clear with what is included in the model, but less so with what is excluded, and why. Credibility is also entangled with modelling purpose. Globally, much research is funded through governments, and models which are unused or duplicated can be seen as a waste of resources, reducing the credibility of research. Communicating upfront with model end-users about pros, cons, costs, and alternatives can alleviate this. However, communicating negative outcomes from model results was a concern, especially if there are strong differential outcomes across stakeholders. Communication and presentation of model outputs can have a significant influence on the perceived legitimacy and saliency of the model. For example, in a cost-benefit analysis of climate action, the costs of action compared to a "do nothing" baseline can lead to the perception that taking action will be at high cost; while the costs of doing nothing (and the resulting economic impacts of doing nothing) may appear more favourable (Koomey, 2013).

Interacting with knowledge holders, particularly in socio-environmental modelling, has serious implications for legitimacy and salience. Consider the perspective of the knowledge holders and what sharing information means for them, and whether it matters to them if that knowledge can be extracted or exposed by the model. This entails thinking about whether it is possible for knowledge holders to share their expertise in a way that is culturally safe and does not leave the knowledge holder exposed once the modeller has left. There are even cases where the choice may be made for knowledge to be lost altogether rather than shared inappropriately. Weir et al. (2024) observe that natural sciences, such as ecology, do not have a requirement to engage with human ethics processes to consider how their research may impact people, including the Indigenous peoples whose lands upon which that research takes place. This leads to Indigenous perspectives and culture often being disregarded in research that is fundamentally concerned with their ways of being. This illustrates the ongoing inequities in biophysical modelling practices that have critical implications for social, political, and cultural outcomes.

### 4.3.1. Considering justice in modelling practices

The concept of justice in modelling arises with recognition of representation. Modelling represents a particular way of representing reality, through a particular onto-epistemology (how our ways of knowing and understanding of reality are intertwined), one which carries a high degree of power and legitimacy in western science and society. Because of this dominant power there is considerable responsibility on the researcher and

research institutions to ensure their work is done transparently, and with the recognition that there are multiple ways of understanding the world (knowledge plurality) and constructing representations of it. Given there are attendant power asymmetries attached to particular knowledges, there is the risk of onto-epistemological injustices (Ottinger, 2023). A modeller unfamiliar with critiquing their problem framing, for example, may risk perpetuating dominant conceptions of the world if they don't consider different ways of knowing - at best possibly inaccurate, at worst harmful. Justice considerations therefore ask the modeler to consider whose knowledge and ways of making sense of the world count, and why. This may give modellers pause to check on their approach, problem framing, assumptions, and methodological choices.

Justice appeared as a frequent concern within the feedback from the workshop participants. As described in Table 3, we distinguished between justice in problem framing, justice in design and outcomes, and justice in information and resources. Justice in problem framing is a form of epistemic justice, where the knowledge of those with experience of an issue and who are affected by it can influence how it is described (Ottinger, 2023). In many cases, different stakeholders may fundamentally disagree on the very nature of a problem, and failing to understand these differences risks creating additional problems and further embedding existing inequities (Valkenburg et al., 2020). Justice in problem framing considers who is included in defining the scope of the questions the model is intended to address, and who is excluded from this process. One response to this is to allow greater inclusion of those likely to be affected by how the model may be used to define the problem and system parameters. Crucially, inclusion is not just collecting information from affected people and fitting it into a pre-formed project design. Inclusion requires considering positionality, engaging with plural worldviews, and empowering people to influence the scope of research questions for epistemic justice (Hird et al., 2023). Collaborative (where those affected contribute to refining the problem framing and project design) or co-created (where those affected work with researchers to create the problem framing and project design) research (Shirk et al., 2012) are two approaches that may encourage justice in problem framing. To be effective, these methods for inclusion also require an awareness of the power imbalances that may exist between those involved, and implications for whose worldviews are given weight.

Justice in design and outcomes considers how ethical issues are identified, addressed, and monitored during the project, identifying who may be affected by the project, and how decisions about these ethical issues are made and recorded. It concerns both procedural justice in how ethical decisions are made and monitored during the project, and recognition justice in acknowledging the rights and values of individuals and groups who may be affected by it (if these forms of justice are regarded as distinct) (Ruano-Chamorro et al., 2022). Collaboration and co-creation (mentioned above) are possible means of fostering justice in design and outcomes, particularly in place-based modelling activities (e.g., Robinson et al., 2023).

Justice in information and resources considers the provenance and use of the data and the models used in the project. It incorporates both distributive justice in how the benefits and burdens of using the data and the model are distributed, and epistemic justice in considering who is represented in the data. Concerns about data provenance and the origins of models are a significant issue in AI ethics, where machine learning (ML) models may become biased if trained using unrepresentative or incomplete data (Srinivasan & Chander, 2021). Explanatory information for datasets and models that describe the motivations for collecting the data or developing the model, the composition of the data, and how data was collected, have been proposed as tools for addressing these concerns (Gebru et al., 2021). One aspect of justice in information and resources is the possibility of 'ethical debt', which occurs when an AI system is designed, developed, and used without actively exploring its potential ethical implications (Petrozzino, 2021). Ethical debt may occur when existing data or models are used in new contexts without reflecting on how the change of context may create ethical concerns for the model that were not present in its original context. This is part of the concern with the 'projectification' of modelling projects, where models may be reused outside of their original context.

Another concept from AI ethics we identified in the reflections and feedback from the workshop is the possibility of 'responsibility gaps' occurring in modelling projects. Responsibility gaps emerge when there is uncertainty over the ethical responsibility for the output of a machine learning (ML) system, since the model makes decisions based on the patterns it has identified within the data used to train it, rather than patterns explicitly programmed into it by its developer (Matthias, 2004). The ML model may be a 'black box,' which may not be fully understood by its developers. The concept of the black box is similarly applicable to complex models (Puy & Saltelli, 2023). This uncertainty about how the model operates creates further uncertainty regarding the level of responsibility that model developers bear for something they do not understand. Setting clear expectations

about responsibility and accountability for the model, and the specific contexts where the model may be used, as well as clearly documenting the assumptions used in developing the model, may assist in addressing this concern. Beyond the model, modellers may question who is responsible for ensuring the findings/outputs are used ethically, and not misrepresented in ways that could cause harm.

### 4.3.2. Fostering a responsible modelling practice and culture

One significant piece of feedback received by the author team after running a similar workshop to the one described in section 2.3 was that a participant with many years of modelling experience "had never considered any of the points […] raised before" in their modelling practice, yet the insights shared and richness of the discussions demonstrated a clear desire to explore ethical issues they weren't yet in the practice of addressing. As societal awareness of model biases and conditionality grows, socio-environmental modellers and their institutions will be increasingly expected to demonstrate responsible modelling practice and exercise a duty of care to the people who are impacted by the results of their models. Even non-medical models can determine life or death, alter human living conditions, or impact other species or environmental entities. One suggestion raised was to question the model even when it 'looks right', to ensure it is correct for the right reasons (and to check assumptions so the underlying dynamics are not misrepresented).

### 4.3.3. Researcher capabilities and responsibilities

The aforementioned feedback and researchers' experience indicates that scientists who become modellers rarely receive training or education in ethics theory nor how to navigate ethical issues of their work. Given the potential real-world implications, this is a problem. Amorocho-Daza et al. (2023) discuss how in the field of system dynamics modelling, ethics is considered, but only in limited ways, and indirectly rather than explicitly. We suggest this conclusion could easily be generalised to other types of modelling.

In addition to broadening research training to encompass ethical considerations, the response to these problems requires something of a culture change from both researchers and research institutions. Engaging with diverse external collaborators, including across cultural differences, requires additional highly attuned, researcher capabilities, or 'practical wisdom' (see Caniglia et al., 2023). Consideration of relational aspects with other humans and the non-human world (Tschakert, 2022; Tschakert et al., 2017; West et al., 2020) is also a critical part of ethical reflection in socio-environmental systems thinking and modelling. Researchers need not only courage to raise concerns or challenge limited ethical reflection, but colleagues who are receptive to changing their practices in a time-pressured research setting. This requires all researchers to support a culture of inquiry and reflexive practice. Modellers need to embrace reflexivity in their practice and be transparent with research questions, model assumptions, limitations, and uncertainty – all endogenous considerations. However, we can also better engage with exogenous considerations, from clear communication of uncertainties in translating model findings, through to fostering an ethical practice in our professional communities.

### 4.3.4. Institutional capabilities and responsibilities

Research and training institutions also have an important role to play by ensuring that ethical considerations are a norm for modelling practice. Institutions have the responsibility and capacity to support ethical practice as part of their social contract with society in establishing the acceptable conditions, culture, and practices through which science, and specifically modelling research, is done. Institutions can ensure ethics are a fundamental part of the training that a scientist/modeller receives. Institutions can establish principles, processes, standards, and norms to support ethical considerations in modelling and provide support towards the additional resourcing (time, capabilities, financial) that may be required for modellers to complete projects while meeting ethical requirements. To be more credible and legitimate, researchers and their institutions should take greater responsibility in considering how models can inform decisions, and potentially advocating for change based upon model results (Dunn & Laing, 2017).

As noted in the Introduction, there are promising signs that ethics is becoming better recognised in modelling theory, but there is always a delay in translating from theory to practice, hence the efforts here to provide practical considerations. While most modellers may be cognisant of these endogenous ethical considerations (even if only implicitly), appropriate institutional support is critical so that modellers can effectively examine the ethical dimensions of their work. Based on our findings, we suggest that modellers can encourage a broader culture of ethical modelling practice, which would assist with managing the exogenous ethical considerations in

their organisations (e.g., acknowledging and addressing consequences of 'projectification'). In this way, the culture change can occur from both top-down and bottom-up directions.

## 4.4 Limitations

We acknowledge that our list of ethical dimensions is far from exhaustive, but represents a starting prompt for modellers to reflect on ethical aspects. Modeller reflection, and ensuing actions, is an ongoing process of learning, tailoring, or refinement across each and every modelling project. Additionally, we recognise that model repurposing was not commonly engaged with in the case studies we examined and thus was not deeply explored in our analyses or reflections. The reflection and guidance on use of FAIR principles by the team working on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change provides an example of how reuse can be done in practice (Iturbide et al., 2022).

## 4.5 Practical suggestions for responsible modelling practice

As noted, these are not comprehensive suggestions. Developing a responsible modelling practice is personal to each modeller, and the below are suggestions for where to begin this journey.

i) For modellers

1. Embrace reflexivity – the questions from Table 1 provide useful prompts for ethical reflection using the credibility, legitimacy, salience principles; however, there are many ways in which to develop a critically reflective modelling practice, including but not limited to considering knowledge plurality, researcher positionality, stakeholder mapping, how knowledge may be co-produced, and engaging with interdisciplinary research teams (Klein et al., 2024; Mochizuki & Wada, 2023).
2. Work through the considerations within the 11 ethical dimensions in Table 3 and seek to understand how and where they apply to your own modelling work and work environment.
3. Embed processes which examine ethical dimensions during project planning for identifying, assessing, monitoring, and managing potential ethical issues across all stages of the project. Try to recognise where ethical issues may arise and develop plans to avoid or manage them ahead of time. Ensure sufficient resources and time are available to carry these out.
4. Notice any discomfort about aspects of the modelling project – it may be an indication of a potential ethical issue (but lack of discomfort does not indicate absence of ethical issues). Thresholds for discomfort may be different for individuals depending on their respective positionalities, and level of awareness of potential issues. Nevertheless, reflecting on personal discomfort can be a good starting point for practicing reflexivity, and can be a rich topic for initiating conversations about responsible modelling with colleagues.
5. Follow best practice in collection, use and publication of data by following FAIR (Wilkinson et al., 2016), CARE (Carroll et al., 2020), or other responsible data stewardship principles (Wendelborn et al., 2023) if appropriate.
6. Seek out other examinations of ethics in modelling to broaden your understanding (e.g., Bennett et al., 2022; Mazzega, 2018; McLaren, 2018).
7. Practice humility: don't assume you know everything, seek out information to better understand any potential ethical questions, and be open to different perspectives. While we all greatly value and recognise the critical role of modelling, we also recognise it is not the only valid knowledge nor means of understanding the world.
8. Lead by example and promote responsible practice from the commencement of a modelling project.
9. Document ethical issues and how you navigate them. Work with your institution to develop awareness and resources to support modelling projects.
10. Be clear in your communication about the project, the model, the issues, uncertainties, and decision-making processes.
11. Don't get disheartened – ethical tensions can be challenging to navigate, so be kind to yourself and each other as you do. Some issues may not be resolvable within your project, but the process of identifying and thinking through ethical issues builds your awareness, skill, and the legitimacy/robustness of your work.

ii) For users of model outputs
    1. Don't use model outputs uncritically – consider how appropriately model outputs can be used for your context.
    2. Be aware of assumptions that were made in the model and be prepared to question them if they are not relevant.
    3. Understand the uncertainty within the model and how it affects the findings and decisions based on model results.
    4. Consider the questions and issues raised in Table 1 and Table 3 in relation to the model. Ensure there are no ethical concerns about the development and use of the model that produced the outputs.

iii) For institutions
    1. Researchers might have limited agency, and personal reflexivity might not be sufficient. Work with teams to understand support needs and responsibility gaps.
    2. Support collective reflexive practices (peer-learning and communities of practice) and be receptive to the role of these in influencing the institutional culture around modelling practices.
    3. Develop clear standards and expectations for staff for how they should navigate ethical dimensions. For example, how does the organisation expect projects to deal with power imbalances amongst stakeholders?
    4. Embed responsible modelling practice by setting up processes and standards that support and ensure identification and navigation of ethical dimensions of projects, e.g., through internal reviews of project plans and/or models prior to publishing. The questions and framings presented in Table 1 and Table 3 can help with this. Ensure time and resources are available for teams to go through these processes.
    5. Organisations need to acknowledge the diverse skillsets and additional time required for ethical reflection throughout the modelling process: where modelling requires external engagement; when modelling research is being co-produced; to manage and work with additional layers of uncertainty, and negotiation of rights, risks, and benefits; and the necessary research translation for effective communication with diverse collaborators.

# 5. Conclusion

The decisions we make as modellers and the operational environments we work within shape model outputs in ways that affect the world around us. While responsible research and innovation requires that we question these effects and the broader societal implications of our work, the day-to-day examination of responsible modelling is not necessarily supported institutionally nor actively considered by modellers themselves. We reflected upon six modelling case studies that span a range of socio-ecological and biophysical systems, using the principles of credibility, legitimacy, and salience to elicit ethical considerations. From the results of a guided workshop with modelling professionals, we identified 11 ethical dimensions encompassing observations and questions critical to the ethical design and use of models. Concerns about justice appear in how modelling problems are framed and designed, the information used to develop them, and in the outcomes that result from using models. We propose practical suggestions to improve the adoption of modelling ethics for modellers, users, and their institutional hosts that are derived from the work herein with support from pre-existing ethical frameworks. The importance of approaching modelling through an ethical lens cannot be overstated: lives and livelihoods are often affected by modelling results in unexpected ways that were nevertheless predictable. Considering these effects before and during modelling is a pre-emptive step for preventing or mitigating harm, with the added benefit of building better models.

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## Supplementary Material

The Supplementary Material can be found online at: https://sesmo.org/article/view/18849/18281.

## CRediT

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