Supplementary Material

Applying an ethical lens for more responsible modelling practice

Supplementary Material A: Expertise stated by workshop participants

- Socioecological modeller, systems modelling, sustainability science/ecology
- Design thinking, human centred problem solving, collaboration
- Statistical and ML modelling; AI for cyber, human-centred AI
- Language technology and human-computer interaction
- Ecology, socioecology
- Compsci and software engineering; formal models of software systems, legal modelling
- Cybersecurity, and applied crypto and ML [machine learning]
- Qualitative models, agent-based models
- Psychology and data science; applications to social media and media
- Ecosystem and network modelling
- Applied ethics
- General modeller, applied maths
- Energy consumption, loads, generation, modelling; building efficiency; energy economics
- Complex systems modelling
- Aquatic systems modelling (coupled nonlinear Ordinary Differential Equations); complex systems science
- Modelling support; digital architecture
- Systems thinking and modelling of socioecological systems
- Biophysical modelling – material fluxes through natural systems
- Digital architecture – technology
- Bioinformatics.

Supplementary Material B: Workshop outline

Workshop data collected through online platform Miro (https://miro.com/).

Warm up activity

Use the sticky notes to make a note of your expertise (e.g., the type of modelling you do, your research field or discipline)

Activity 1: Hypothetical case study

- Rural town, heavily impacted by Black Summer bushfires & later floods.
- In town there was a general store, a pub, a café and restaurant popular with tourists; a small art gallery, a small primary school and a camping and caravan park. Around the town there are a couple of large farms, and a luxury nature resort, and state forest and national park. Some of these were heavily impacted by the disasters.
- Socio-economically diverse: includes treechangers that have remote work, and more disadvantaged folks with low employment, Traditional Owners. Also differing relative impacts from disasters, e.g. levels of property ownership; impact on income - local vs external sources of income; insurance levels.
- Within the town, there is still a lot of grief and anger over lost lives, homes and livelihoods. Different people also have different ideas for the future of the town, and their place within it.
- Government funding provided for modelling to assess risks and determine future of town.

- Funds to create social-ecological model to explore 2-4 scenarios, e.g.:
  1. Business-as-usual rebuilding of the town (same as before disasters)
  2. Alternative scenario: rebuilding with much higher building standards against fire and flood (which may include compulsory acquisition of unsuitable property)

Prompt question
What ethical considerations might arise from this case study? Use sticky notes to add your thoughts below.

Activity 2: Interest/influence matrix

1. Stakeholder mapping – brainstorm who has an interest ('stake') in the modelling
   a. Possible stakeholder roles include: co-design/ co-development/ co-delivery role; project champion; provider of resources; affected by outcomes; interested bystander; end user (but not involved?)
2. Place stakeholders identified onto the interest/influence matrix (Figure B1)

Prompt question
After the stakeholder mapping exercise, now what ethical considerations do you think might arise from this case study?

Activity 3: generating list of ethical issues

Prompt question
What are ethical issues that modellers would ideally engage with when designing, developing, and delivering a modelling project.

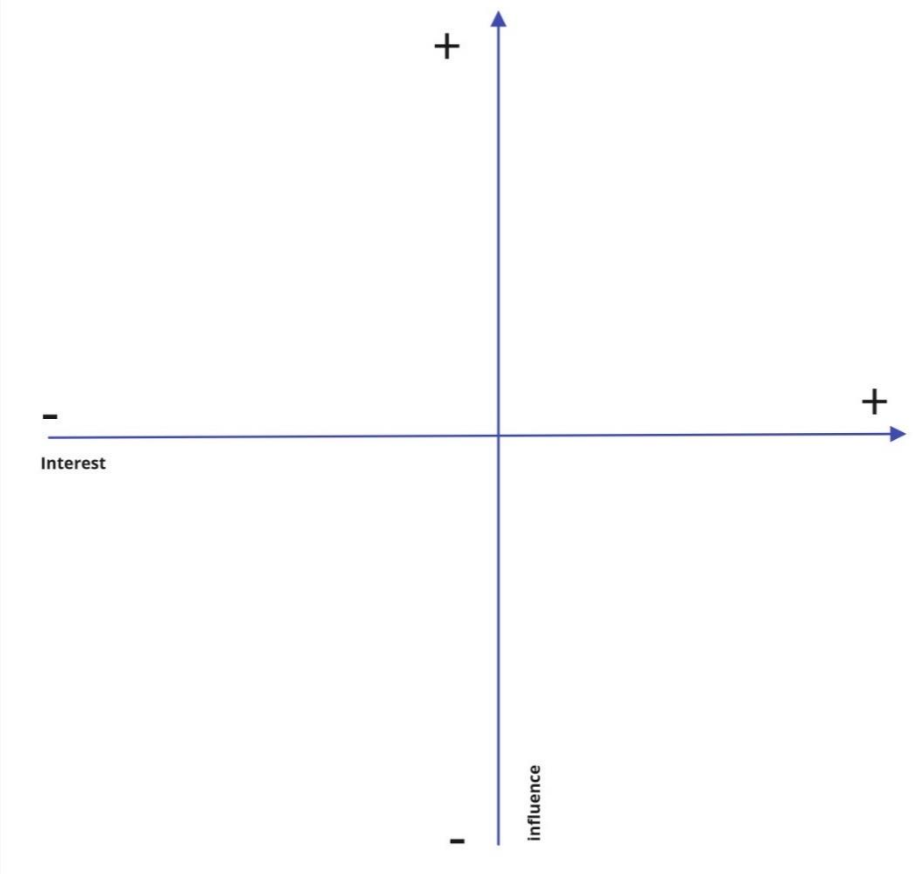

Figure B1: An interest/influence matrix. Interest is one axis and influence is the other. Stakeholders are placed on the matrix with reference to how much interest they have in the modelling project, and how much influence they have on it, e.g., if the interest was high, but influence was low, then the stakeholder would be placed on the bottom right quadrant of the matrix.

Supplementary Material C: Thematic analysis methods

Thematic analysis of the set of considerations co-produced in the workshop was conducted independently by four members of the co-author team (KS, NG, DD, DW), each using their own process and perspectives with an inductive approach (MacFarlane & O'Reilly-de Brún, 2012). Three of the four conducted their analysis by grouping the participants' observations into themes, while the other applied multiple thematic labels to each observation. Three of the four grouped only the observations created in the dedicated co-production activity, while the other additionally included reflections voiced earlier in the workshop, if they provided relevant additional considerations or context not captured in the final set of observations.

Synthesis of the themes was carried out by three members of the co-author team (NG, DW, RS): two who had contributed their own thematic analysis, as described above, and one who had not. Each of these three co-authors studied all four thematic analyses, reflected on commonalities, differences, what they liked from each analysis, and developed initial ideas about how the four sets of themes could be synthesized. They then met, shared their reflections, and mapped the themes against each other to develop a final set of themes that captured each of the themes identified individually. Additionally, one co-author suggested a different dimension that could be applied, that intersects with each of the themes.

Supplementary Material D: Workshop data: results of thematic analysis

Examples of ethical issues and considerations for modellers drawn from the workshop co-production exercises. The examples are arranged according to the emergent ethical dimensions identified in the thematic analysis. Some ethical issues are relevant to multiple dimensions. Some statements have been lightly edited for clarity and context.

1. Justice in problem-framing

- Who is framing the problem and is there a process for eliciting multiple, diverse perspectives on the problem framing (especially in 'wicked' problems where the problem definition/framing itself may be contested)?
- Representation- who's conceptualising the system?
- Question asked will shape what you get.
- It starts with problem framing - if framed without considering impacts on diverse groups - then outcome will be flawed
- Framing a project will end up excluding some dimensions/resources/stakeholders from consideration, even though they will potentially be subject to harms
- Is there a justice or equity lens on the work?
- Recognise that even when a model is purely about biophysical processes, there are these ethical dimensions
- Who is affected? Who might be impacted by the model?
- How you do this modelling is going to strongly affect the results you get - choice in how you do it will flavour what you find.
- Ensure that no-one is worse off as a result of the model outcomes - is this even possible?
- Not high stakes for the modeller - just one project for them and they are not personally affected by outcomes (while that also provides some independence)? If there are unwanted consequences down the track the modeller is long gone? Or maybe risks of being taken to court years later?
- [Modellers can start by] acknowledging their positionality and power
- Testing assumptions across all stakeholders
- What researchers could do: – they could sit down and do a similar exercise as we did today – it doesn't need to take long, or be perfect/comprehensive. But taking time to think about issues important.
- How to include stakeholders without a voice? Children, animals, plants etc.

2. Project planning: justice in design and outcomes

- Is there a justice or equity lens on the work?
- Who is responsible for the ethical considerations? The modeller, project lead, key stakeholders?
- Identifying the 'responsibility gaps', and if/how those gaps can be reduced
- Different issues at different stages in modelling- so can't just do it once/upfront and think it's done.

- Who is framing the problem and is there a process for eliciting multiple, diverse perspectives on the problem framing (especially in 'wicked' problems where the problem definition/framing itself may be contested)?
- Does a particular methodological (modelling or collaboration methods) decision impact trust, credibility or legitimacy of outcomes?
- Think about the biases in your model: biased data, preconceived ideas, inability to capture all processes
- How to balance priorities between end users of the model and communities/groups who may be impacted but have little influence on how model outputs are used
- How will stakeholders be impacted?
- How to include stakeholders without a voice? Children, animals, plants etc
- What are the best ways to communicate to different stakeholders? (e.g., Government, other scientists, the public)
- Is it ethical to model unrealistic outcomes? Or good to explore a range of possibilities because who knows what the future holds?
- How to measure trade-offs?
- How [will] risk and uncertainty [be] determined and communicated?
- Distribution of risks/benefits arising from outputs across the setting/system
- Have you checked system conceptualisation (before and after outputs generated) with stakeholders/ collaborators?
- There are often no right answers. Some ethical tensions/trade-offs are not resolvable, especially within the scope of a single modelling project. But if we can create a culture of considering ethical issues, and solutions, then even if we end up making the same modelling choices that will be better than making those decisions blindly.
- Stakeholder influence in shaping modelling vs influence on the system
- [Do check-ins:] Do you have a bad feeling in your gut about this? Use [a community of practice] as a sanity check when encountering problems

3. Ethical engagement

- Doing responsible co-production with stakeholders
- Transparency in methods and problem framing and assumptions
- If people involved in data collection- how do they benefit from being involved
- How risk and uncertainty are determined and communicated
- Being transparent when talking with a sponsor or client about what the model can do and what the assumptions are behind it
- Testing assumptions across all stakeholders
- Natural in these systems that groups that are difficult to work with will be lower down priority list of people you want to work with, and they may be inherently marginalised because of that (easier to work with one company rather than 200 farmers, for example)
- Trying to maintain an 'unbiased' viewpoint, and trying to capture everyone's problems in the model. Often in these cases you'll get big players pushing an agenda of what they want modelled.
- How to balance priorities of different interests.
- How to empower stakeholders who have low influence?
- Power imbalances between stakeholders
- Decolonisation of inputs into model - ensure involvement of Traditional owners
- How do we ensure that we have included all stakeholders?
- Risks to non-participants arising from the study
- People who decline participation, don't provide input, won't be well represented and may be disadvantaged, e.g. Right to object to being modelled (even by non-"participants")
- Stakeholder influence in shaping modelling vs influence on the system

4. Model development

- Using the right type of modelling for the problem we're trying to solve
- Modeller has higher influence in deciding what assumptions to make - ethical considerations between tension of assumptions made and whether those assumptions can be realised in practice.

- If a different modelling group, or researchers from a different discipline/school of thought were to do this work, would their model be very different to mine? (Question about structural uncertainty.)
- How detailed is ecosystem representation - and what is the model skill in predicting their dynamics (complexity-tractability trade-off)
- Choice of scale - spatial, time etc affects results/ outputs
- Am I leaving out an important variable or process?
- Think about the biases in your model: biased data, preconceived ideas, inability to capture all processes
- Honest confrontation with unknowns - be wary of pretending that irreducible uncertainty can be reduced.
- Groups impacted in diverse ways; differential impacts across stakeholder groups/ individuals. Risk potential of not capturing everyone's interests in the model. How to prioritise that? Risk that groups' needs not well represented in the model.
- What if modelling makes assumptions about what is possible without considering real-world constraints (e.g. Cost). (For example, if model assumes building company can rebuilt at a certain price that turns out to be incorrect.)
- What are the consequences of incorrect model specification?
- What are the consequences on suboptimal model parameterisation?
- Representing inequalities in the model somehow (e.g., elderly, poor)

Scenario development

- Make model and scenario assumptions transparent (they may be hidden in the code or in what we expect from the future)
- Need to explore different scenarios in the modelling
- Can we use more creative solutions to solve the problem?
- Is it ethical to model unrealistic outcomes? Or good to explore a range of possibilities because who knows what the future holds?
- Scenarios - can't have whole buffet of scenarios. Lots of uncertainty of predicting the future. When there is lots of uncertainty its harder to communicate

5. Justice in information and resources

- When re-purposing a model, how different is my research question from the original one that the model was developed to answer. What are the potential consequences of that?
- Can you trust your input data? Is it ethically sourced?
- Where and who the data is coming from to run the model
- It's probably not feasible for a modeller to be across the ethical dimensions of all the data being used in a model, as well as the system being modelled. Could there be a framework / database to draw on?
- What if an integrated modelling exercise involves many different models, or modelling components, and there are varying degrees of confidence in these different components? (e.g. it's possible to combine all the models/components and produce results, but there are some highly uncertain processes/components/models involved)
- Should we censor data (e.g. inputs into LLMs)? Who decides what should be omitted?
- Doing responsible co-production with stakeholders
- If people involved in data collection- how do they benefit from being involved

6. Characterising uncertainty and limitations

- If a different modelling group, or researchers from a different discipline/school of thought were to do this work, would their model be very different to mine? (Question about structural uncertainty.)
- What if an integrated modelling exercise involves many different models, or modelling components, and there are varying degrees of confidence in these different components? (e.g. it's possible to combine all the models/components and produce results, but there are some highly uncertain processes/components/models involved)
- Honest confrontation with unknowns - be wary of pretending that irreducible uncertainty can be reduced.
- Think about the biases in your model: biased data, preconceived ideas, inability to capture all processes

- Make model and scenario assumptions transparent (they may be hidden in the code or in what we expect from the future)
- How detailed is [the] system representation - and what is the model skill in predicting their dynamics (complexity-tractability trade-off)
- Choice of scale - spatial, time etc affects results/ outputs
- When re-purposing a model [or data], how different is my research question from the original one that the model was developed to answer. What are the potential consequences of that?

7. Evaluation of outcomes

- How should we evaluate performance of scenarios relative to diverse values
- How would the different socio-economic groups be impacted by each scenario?
- Ensure that no-one is worse off as a result of the model outcomes - is this even possible?
- How to balance priorities between end users of the model and communities/groups who may be impacted but have little influence on how model outputs are used
- Distribution of risks/benefits arising from outputs across the setting/system – [is it] equitable?
- How [can] risk and uncertainty be determined and communicated
- Which uncertainties in your model impact what things (stakeholders, etc)?
- Make transparent the tradeoffs between immediate and future impacts and who benefits from which; costs [and] benefits in short vs long-term.
- Trade-off in scenarios for environmental vs human outcomes
- Will it create further division [or] disenfranchisement of people of lower socioeconomic status?
- What happens if decisions based on your model are not realistically implementable (eg, the cost is definitely too much)?
- What do you do if you disagree with the model outputs?
- What if an integrated modelling exercise involves many different models, or modelling components, and there are varying degrees of confidence in these different components? (e.g. it's possible to combine all the models/components and produce results, but there are some highly uncertain processes/components/models involved)
- Trade-off in scenarios for environmental vs human outcomes

8. Clear communication

- How to responsibly communicate model results?
- How can outputs be delivered in an inclusive way? E.g. not just a report
- Clearly communicating uncertainties, assumptions and limitations of modelling, BUT ALSO communicating the uncertainties that exist in the alternatives.
- Communicating implications of trade-offs, e.g. for environmental vs human outcomes, for different socio-economic groups
- How can you best communicate that your model is wrong, but perhaps useful?
- Delivery has to include transparency about the assumptions
- Make transparent the tradeoffs between immediate and future impacts and who benefits from which
- Make model and scenario assumptions transparent (they may be hidden in the code or in what we expect from the future)
- Models are seen as less reliable because we do our best to make the uncertainties transparent (c.f. not made explicit in mental models) -We aren't going to solve a problem or come up with perfect solution. But we can improve on the alternatives'
- Scenarios - can't have whole buffet of scenarios. Lots of uncertainty of predicting the future. When there is lots of uncertanity its harder to communicate.
- Designing delivery / communication to prevent future misuse of model: Preventing a good model being used for something unintended

9. Model repurposing

- Preventing a good model being used for something unintended; Designing delivery / communication to prevent future misuse, [e.g.]clearly communicating uncertainties, assumptions and limitations of modelling
- When re-purposing a model, how different is my research question from the original one that the model was developed to answer. What are the potential consequences of that?

- What if an integrated modelling exercise involves many different models, or modelling components, and there are varying degrees of confidence in these different components? (e.g. it's possible to combine all the models/components and produce results, but there are some highly uncertain processes/components/models involved)

10. Model repurposing

- Organisational positionality and responsibilities

Clarifying organizational positionality, and scope of responsibilities for modellers within it

- What can modellers do if they feel discomfort about ethical concerns (e.g. is it ok for them to turn down a potential project or is there pressure to bring the money in for their employer)?
- What can the modellers do if they find problematic ethical issues in their results/findings?
- Clarifying boundary between ethical modelling practice vs being seen as delving into political issues. So modellers know where they have scope to make projects more ethical, and feel confident in not overstepping or pushing their own values
- Navigating tensions between funding, managing reputational risks, and maintaining professional standards. Never black and white
- Difficult for modellers to push back on interests of those commissioning/funding the model? Who do the modellers serve - the impacted community or whoever is paying the bill for the modelling?
- Guidance for navigating power imbalances amongst stakeholders – e.g. organisational positionality on how to include disadvantaged stakeholders [in different contexts]
- Ethics in operational settings of models, what are the boundaries when faced with challenging situation such as safety and environmental disaster.

Resourcing / infrastructure

- Providing training: with proper [ethics] training modellers are in a very good position to do a great job of it. We understand and can communicate the uncertainties and limitations [of a model and findings].
- Computing infrastructure: resources to train models sustainably (green data centres etc)
- Providing guidelines/guidance: having a list of guiding prompts, along with clarity about organizational positionality on some of the tensions, would be really helpful, especially for those just starting out.

11. Fostering an ethical modelling practice and culture for modellers

- Recognise that even when a model is purely about biophysical processes, there are these ethical dimensions
- Acknowledging their positionality and power
- Use [a community of practice] as a sanity check when encountering problems
- There are often no right answers. Some ethical tensions/trade-offs are not resolvable, especially within the scope of a single modelling project. But if we can create a culture of considering ethical issues, and solutions, then even if we end up making the same modelling choices that will be better than making those decisions blindly.
- Do you have a bad feeling in your gut about this?
- Is it better to work on a model that you feel uncomfortable with so you can influence the outcomes or walk away?
- clarifying boundary between ethical modelling practice vs being seen as delving into political issues. So modellers know where they have scope to make projects more ethical, and feel confident in not overstepping or pushing their own values.
- What do you do if you disagree with the model outputs?
- Should we censor data (e.g. inputs into LLMs)? Who decides what should be omitted?

Supplementary Material E: Case study narrative reflections

Case study 1: Drivers of malaria risk under climate change – participatory systems model

Stages of modelling

The aim of the model was to understand the biophysical and socio-ecological drivers of malaria risk in a changing climate. The model was premised on current evidence which projected an increase in malaria transmission in highland areas of East Africa from biophysical modelling of climate change and malaria risk under different warming scenarios. However, malaria is also a disease that is influenced by socioeconomic, biological, and demographic factors and there was limited evidence in literature regarding how these factors influenced the risk of malaria infection. Therefore, this presented a large degree of uncertainty regarding the level of risk attributable to climate change impacts. By integrating biophysical and socio-ecological and socio-cultural drivers, the model aimed to understand the array of factors driving exposure and vulnerability to climate change and malaria risk from a socio-ecological systems lens.

Model parametrisation relied on a variety of data inputs including expert and stakeholder knowledge, secondary data sets, and climate change scenarios, through a participatory systems modelling approach. Stakeholders were engaged at different stages and levels of the model development. Stakeholders included thematic experts, academia, NGOs, policy makers from health, environment, agriculture and forestry, international organisations, local community organisations and community members. Not all stakeholders were used to inform all parts of the model, instead stakeholders were grouped into thematic groups that aligned with the research aims and objectives and their inputs into the model were systematically included through these thematic groupings. Three thematic experts (selected based on publication history and deep knowledge of the field) were consulted (expert reference group) throughout the modelling process to review and validate research findings.

Model construction, testing, and refinement

The initial conceptual system model was quite comprehensive, describing 42 system variables that corresponded to four aspects of climate change and malaria risk, i.e. exposure, vulnerability, hazard, and response/adaptation. Source identification for the variables was broken down as follows:

- Literature Review and Expert Consultation: 36 variables identified (21 biophysical, 15 socio-economic)
- Focus group discussion and stakeholder interviews: further six variables identified (socio-economic)

Structural analysis using the Cross-Impact Multiplication Method (MICMAC®) was used to reduce the system from 42 variables to 27 key variables. Further, the criteria outlined by (Chen & Pollino, 2012), was applied to reduce the model further to a parsimonious set of 20 key variables that were deemed manageable, predictable, or observable at the community level.

The model-building phase was an iterative process of parametrisation, testing, validation (with expert reference group and key stakeholders), and refinement over a few cycles until the final model was validated as an accurate representation of reality.

Findings

The outputs of the model were disseminated through scientific papers and reports, conference presentations as well as a report back to key policy makers for distribution to the community. Due to time and money constraints, in-person feedback to the community was not feasible.

Case study 2: Local scale pathways to sustainable futures – participatory systems model

This was a project to explore planning and implementation of pathways to the Sustainable Development Goals (SDGs) at the local scale in a small regional town. It was conceived from the outset as a bottom-up, community driven project, which was to be co-produced with local stakeholders. It took the form of a typical scenario modelling process, using a multi-sectoral system dynamics model (IAM) to examine locally relevant sustainability questions. The experts in this project were the members of the township's community and they contributed through the provision of knowledge and co-development of outputs.

The initial stages of information gathering served to develop researcher understanding of the problem context; this contributed to boundary framing of the socioecological system and development of drivers of change and dynamic hypotheses. However, this also included some sensitive information, such as experiences of poverty and inequality, which needed to be dealt with in a respectful manner and thus represented thoughtfully in the model. The creation of a range of narrative scenarios provided a framing for how to do this, with drivers of change being expressed differently according to the scenario conditions. These conditions were broadly aligned with the prioritisation of the three dimensions of sustainability (economic, social, environment), so, for example, a scenario which did not prioritise the social dimension would have poor outcomes for social drivers such as inequality, health, and poverty.

The model, containing 12 interacting sectors of the socioecological system, was constructed independently by the modeller using the information collected through participatory means, and iteratively improved through testing and validation. A participatory systems mapping workshop was conducted part way through this process to identify the interconnections between the system sectors and this information was used to refine the model. The model was fully documented with over 100 pages describing variables, assumptions, conceptualisation, and data sources.

Some ethical concerns expressed by the modeller include: worry over capturing all relevant data to accurately describe the system, particularly over inadvertently disenfranchising or excluding people; model wasn't fully co-designed so modeller choices may have left out important information, or misrepresented processes (especially where there were conflicting views captured in the data); and, modeller reached the end of their contract without having formally handed back results to the stakeholders, leaving the project essentially unconcluded (project eventually wrapped up but a full 18 months after modeller had left the position and needed to take time out to return for final presentation of results).

Case study 3: Food packaging impacts – causal loop diagrams

The study aimed to understand how to reduce food packaging in food systems. The study followed the following modelling steps: (1) problem articulation, (2) dynamic hypothesis formulation, (3) simulation model formulation, (4) model testing, and (5) policy design and evaluation (Sterman 2000). The initial framing involved analysis and synthesis (Barton and Haslett 2007). The framing stage was particularly important in order to understand why problematic patterns and trends in the use of food packaging exist. To explore the reasons that led to these problematic patterns and trends, we had to reflect and decide on a clear timeframe to analyse. Plastic production and plastic packaging have exponentially increased since the 60s, therefore, a time horizon from the 1960 to the present was established to conduct the behaviour over time analysis (i.e., problem articulation). We then analysed various food systems and societal trends to gather information about food systems' changes. The trends analysed explored changes in, for example, urbanisation, food consumption patterns and globalisation. The trends analysed represented the archetypes used as the basis to build the first causal loop model (model construction), a dynamic hypothesis that explained the growth in food packaging use. International databases have been used to gather historical data. Some countries had more data availability than others, such as in terms of time survey and food time data. This is a modelling challenge that reinforces the attention and exploration of countries that have the capability to collect data, leaving behind more disadvantaged countries or realities.

In addition to the exploration of archetypes, the results of a narrative literature review also helped build the causal loop diagram (CLD). The CLD was built with the goal of presenting the feedback loops that explain the behaviours and system structure responsible for the increased use of food packaging. The CLD has then been validated against primary data collected through semi-structured interviews held with experts working within and conducting research on food systems in Australia (e.g. food packaging producers, supermarket representatives, government stakeholders, and academics). This was an important step to establish confidence and usefulness in the model (testing and refinement). However, stakeholders had limited time availability and were interviewed individually, meaning that the modelling process did not create a space for discussion and confrontation among stakeholders. The model was validated, and the process improved the models' outputs, however, it might be important to create change along the process, by, for example, connecting different stakeholders and creating safe spaces to explore systemic solutions.

The modelling process has been useful to explore the drivers of packaged food, and it contributed to the literature by pointing out globalisation, urbanisation and changes in household dynamics as some of the main systemic drivers that influence the dependence of packaging in food systems. The findings have been published in academic journals and on other platforms (e.g. The Conversation) (report findings). Additionally, the researchers have been invited to share insights of the study at events, conferences and in the media. Sharing the findings has been a useful and important step of the study as it helped shift the conversation from post-consumer actions (e.g. recycling) to rethink deeply the purpose and structure of food systems and our economy. For example, packaged food use would be reduced if the growth-driven globalisation is reduced or if time poverty in modern societies is tackled, so that individuals have more time for food work, instead of relying on convenient processed packaged food. Nevertheless, the study's main critique is that agency has not been thought about in the process. Who’s responsible for influencing and changing the system's various sub-systems, variables, or feedback loops? This lack of reflection and integration of agency meant that, for example, the call for action to solve the problem was lacking when reporting the findings. In times of poly-crisis, having a clear call for action with attached agency and responsibility might be a necessary step to integrate into modelling processes, although, due to the nature of studying wicked problems, this might result in a difficult task. Perhaps, participatory exercises could help identify stakeholders’ responsibilities to act on the system's leverage points.

Case study 4: Hypothetical case study based on modeller experiences – biophysical modelling

There are well-known ethical considerations that arise in modelling biophysical processes, in the absence of any complications associated with modelling human dimensions. Consider two hypothetical cases:

1. Hypothetical case A involves biophysical modelling for increasing scientific understanding only, with no immediate intention to inform societal decision-making etc.
2. Hypothetical case B involves social-ecological system modelling with the purpose of informing decisions within that social-ecological system.

The table below outlines that ethical issues are involved even in Hypothetical Case A, but Hypothetical case B brings additional ethical issues.

	Hypothetical Case A - biophysical modelling for increasing scientific understanding only, not for informing decision-making etc	Hypothetical Case B –social-ecological system modelling with the purpose of informing decisions in that system
What does the model represent?	Only physical things that can be quantitatively measured are represented in the model.	Everything in Case A, plus phenomena such as people's values, economic and social influences, mental models, and anything else that is perceived to have an influence in the system.
What kind of question is the model designed to address? (Model purpose)	To what extent is the model consistent with observations of measurable physical phenomena?	Where and how can people intervene in a system to achieve desired outcomes?
Human choices	• What to include or not include (what is in/out scope)? • Who is involved in undertaking the modelling, and whose knowledge is considered relevant? • What kind of model is appropriate to represent the system of interest? (e.g., process-based differential equations, data-driven statistical inference, integrated models coupling model components of different types) • How to handle differing perspectives? • What model experiments to conduct? • What to do about sources of uncertainty? • How to interpret model results and evaluate their reliability? • How to communicate the findings? • How will the modelling be updated and corrected as more is learned?	Everything in Case A, plus • Whose knowledge or perceptions are included or not? • How to characterise interactions between different 'currencies' (e.g., some variables may have biophysical units of mass and energy, while other variables may be in dollars, or non-measurable influences) • How to elicit and represent people's values (and other incommensurables) • How to distinguish between people's perceptions and 'reality' and how to characterise the interactions between the two (e.g. how people think the system works may not be how the system actually works, but their mental models do influence decisions and have real impacts on the system) • Who is the modelling for and how will it be used?
Issues that raise ethical concerns	• "Equifinality": there may be multiple acceptable models for representing a biophysical systems (Beven, 2006). Furthermore, the space of acceptable models may be too large/high-dimensional to characterise. • A consequence of equifinality is that models can only be confirmed, not validated (Oreskes et al., 1994) • Even observations are problematic: observations are theory-laden (Hanson, 1958) • Confronting models with data and confirming dynamics is made more difficult in nonlinear systems (e.g. to confirm chaotic dynamics you need to compare chaotic attractors rather than comparing exact time course of trajectories). • Models are open systems and so can be tweaked and adjusted to be consistent with data (Oreskes et al., 1994).	Everything in Case A, plus • "Cosy nest." Decision maker wants modelling to justify their decisions. Modeller wants real-world applications to demonstrate impact and relevance. Modelling work can be conducted that gives the appearance of both, while achieving neither. This is particularly the case if there is a long time-lag between model results and any means to verify the results. • Ideologies can be embedded modelling assumptions (e.g., integrated assessment models that assume GDP can be decoupled from material growth) • There is potential plurality at all stages of the inquiry (equifinality amped up a level) • Framing assumptions are not amenable to being scrutinised through technical assessment (e.g. if modellers have been commissioned by a government agency to develop a

	• The previous point leads to a trade-off between parsimony and realism (Oreskes et al., 1994) • Induction/extrapolation issues (e.g., model confirmation against historical dataset doesn't mean it will hold when projected forward or used to extrapolate beyond the calibration context). • Once a group is committed to a particular model and its results, it's harder to foster open-minded critical reflexivity and engage with critical peer review in good faith. • If model developers are explicit about model uncertainties or limitations, sometimes it means their modelling will be viewed less favourably than models developed by modellers who do not communicate limitations of their model. • What happens if the modelling is taken and used in a different context outside the purposes for which it was designed? • 'Projectification' – once a project is finished there are barriers to revisiting the work, making corrections, updating in the light of new knowledge.	methodology for assessing environmental offsets, they may have limited opportunity to challenge the validity of offsetting – or risk not being commissioned to do the work if they wish to be free to provide critique of underlying ideology)

Case study 5: Biogeochemical cycles – general examination of biophysical carbon models

Modelling in biogeochemical cycling ranges in complexity from data driven curve fitting exercises (Figure E5a) and proxy based, but still measured, flows (Figure E5b) to net movements through the system based on measured data and experimentally derived estimates (Figure E5c) and complex models comprising many sub models containing measured, modelled, and 'best educated guess' data. Complex models are largely limited to net movements of carbon through systems due to methodological constraints; the decisions on what inputs to include (and where to source the data from) have meaningful impacts on the modelled outcomes. Soil biogeochemical models will often contain several 'best educated guess' constants that may generate significant mathematical leverage on the modelled movement of material through the system. Partitioning factors, for example, which determine what proportion of carbon is lost as carbon dioxide are estimated values stemming from experimental data that strongly affect flows within the model.

At the largest scale, biophysical carbon models are used for estimating global carbon fluxes, transformations, and pools and have long been used as evidence for anthropogenically forced climate change (e.g. (Hoffert 1974)). They are used in national accounts to track sectoral contributions to carbon emissions and sequestrations (United Nations 2024) and as a monitoring tool for economic incentives to meet policy directives (e.g., Australia's Emissions Reduction Fund). However, from the perspective of soil carbon monitoring, an overreliance on carbon stocks makes extracting useful information at the landscape unit (or paddock unit) difficult as spatial variation is high and carbon compounds are not necessarily stable even once they have been incorporated into the soil organic matter. Downstream use of model outputs, or repurposing models, includes risks wherein known error within the model processes or outputs are not accurately represented in later use thereby generating unreasonable certainty in the results.

Ethical considerations are not typically in the forefront of model developers or model users minds for purely biophysical models. This may be due to a belief or assumption that such models are 'pure science', unblemished by the biases and values of people, and are therefore inherently credible. The intersection of biophysical models and human activities, policies, and economies is where the ethical nature of such models becomes more obvious, however the model framing, structures, and parameters contain inherently ethical concerns even though they are not immediately obvious.

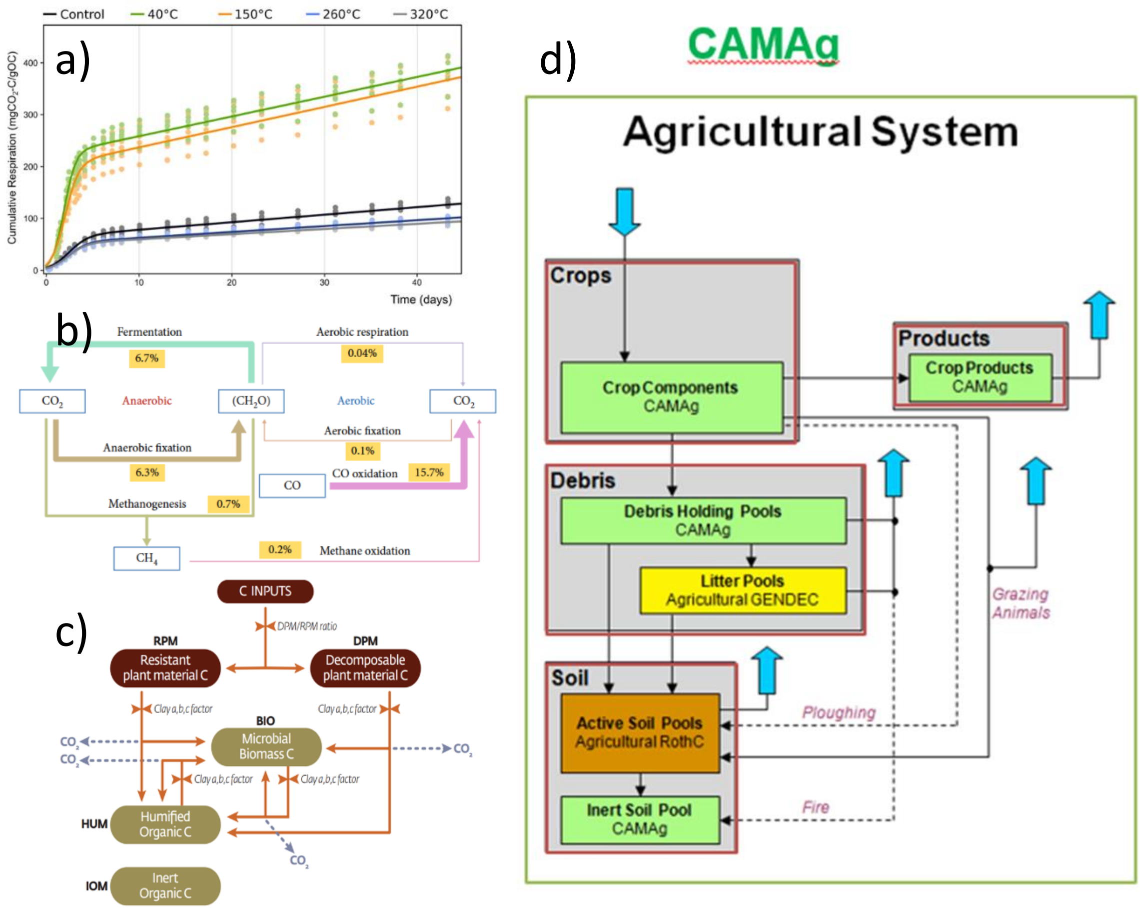

Figure E5: a) Organic matter decomposition – modelled cumulative respiration based on experimental results; image from Stirling et al. (2020). b) Soil carbon cycling potential based on marker gene presence in the bulk soil microbial biomass; image from Ma et al. (2021). c) Roth-C pools and flows – the base model on which many modern carbon models are based. Flows and pools based on net movement; image from FAO (2020). d) CAMAg model for carbon flows in agricultural soils; image from Karunaratne et al. (in prep). Comprising multiple sub-models and requiring multiple inputs from current and historical measured and modelled data.

Case study 6: Influences on contemporary customary harvesting – qualitative conceptual model

In response to the prompt questions from the CLS framework:

What is the aim of the model?

The aim of this qualitative modelling activity was to attempt to synthesise extensive qualitative material into a visual means of conceptually illustrating the drivers of freshwater customary harvesting (as specific to a community remote Aboriginal Australia), in the context of future climate-driven impacts. This was one means (among several) of representing the work to highlight the drivers of decision making and adaptive capacity of contemporary freshwater customary harvesting.

Whose or what kinds of knowledge is most readily accepted by decision makers?

Within the project, the decision makers were the researcher (non-Indigenous) and Indigenous lead collaborator. All work on country was conducted under guidance and direction and approval of this lead collaborator. There is a clear power asymmetry in whose knowledge is most readily accepted by end-users, non-Indigenous decision makers, given the history of Indigenous people's marginalisation globally and in Australia. The research was conceived because these First Nations knowledge and experiences of change hadn't been well-recognised, heard, or readily accepted and it was a topic of clear concern and interest for the First Nations people in this region (thus salient). For this work to be credible, it relies on the technical knowledge of the modeller constructing the model being adequate, and for the work to be legitimate, it requires that the Indigenous knowledge underpinning it is culturally authorised and contributed through ethical and appropriate methods. Meeting ethical research requirements in this instance is a multi-scalar thing, from the institutional level (university ethics approval), local organisations (e.g. prescribed body corporate research approval), to the personal endorsement via positive working relationships to provide legitimacy of the research program. In terms of this activity, the researcher (non-Indigenous) made the decision as part of various analysis methods to test a conceptual modelling representation of the qualitative data. This is something that would ideally be shared and discussed back with the local knowledge holders to validate the findings.

What is the role of participation in supporting credibility and what strategies exist to communicate and translate across scientific/non-scientific communities?

In this instance, participation is essential and not just participation- work such as this needs to be co-produced, from the conception, throughout the research process (e.g. see guidance of frameworks like AIATSIS Research Protocols and FAIR/CARE etc). Here the work arose from a direct concern from First Nations land owners for the potential loss of culturally valued freshwater species (kin) and Country, with future sea level rise, so it was directly relevant and desired by these leaders. This collaborative effort gives the research not just approval, but local legitimacy. However, engaging deeply with ethical considerations of participation was central ensuring culturally appropriate knowledge holders are identified as defined by local authority, not by external sources or researcher assumptions (e.g. perhaps incorrectly based on English language competency, or western means of recognising people of appropriate 'authority'). The constituents of particular 'communities' (e.g. clan groups) may not align with geographical communities or the same geographical area. Getting 'who speaks' or provides the local knowledge wrong, risks the legitimacy of the research and its likelihood of being adopted. It also risks perpetuating historical legacies of negative research experiences for Indigenous communities or participants.

Understanding these nuances as an outside researcher coming in requires locally-led research collaboration and asks of the researcher to justify their standpoint, or position, for being there in the first place. This requires cultural competency, and skills including deep listening reflexivity on the part of the researcher.

How are experts defined and identified?

The process of defining and identifying experts has to be Indigenous-led. These individuals were identified via the prescribed body corporates initially, and then often through snowballing from TO and elder recommendations, identifying those individuals engaging with customary harvesting.

How are the benefits or outcomes of the application of knowledge demonstrated to the wider public?

Not undertaken at this stage, but ideally through scientific papers. This is necessary if the benefit and outcome is to influence adaptation planning or policy related to remote Indigenous Australia or potentially protected area management e.g. via recognition through Healthy Country management plans.

Does CSL framing ask how any potential risks of engaging with the research are distributed? e.g. how are people affected at different scales?

Potential risk here is the desire to trend towards the universalising nature of modelling activities. Presents risks for other communities or cultural groups if decision makers pick up the findings and try to apply it universally or at inappropriate scales.

Strong caveats need to be communicated clearly that the results are for this locale and cultural group only. Findings may or may not align with the experiences of other cultural groups engaging in similar practices. However, there is value in offering a context/case for comparison or consideration by other groups with similar concerns or wishing to do similar work to increase understanding and recognition of a marginalised practice.

There are risks also to participants in (external, non-Indigenous) researcher not adequately understanding cultural complexities or adequately representing local Indigenous world view/ mental model of drivers and determinants relating to customary harvesting practice. But this is where co-production processes ideally allow for iterative discussion and refinement or correction of the conceptual representation.

Supplementary Material F: Synthesis of case study reflections

Table F.1: Summary of ethical issues and questions raised from modeller reflections, aligned with ethical considerations identified from the workshop (main manuscript Table 2).

Ethical considerations	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case study 6
Justice in problem framing	Information that was deemed useful by policymakers or researchers/experts was sometimes not what the community expressed as useful. Involving those most impacted vulnerable to the risks in the research through a co-production process can facilitate better understanding of the problem and therefore the data/information needed	Were the conflicting views expressed by stakeholders adequately represented through flexibility of scenarios?	Post-hoc analysis identified that omission of agency from the model limited its effectiveness, so should this element have been considered at the problem framing stage? Was its omission due to stakeholder intervention?	Who is involved in undertaking the modelling, and whose knowledge is considered relevant? How to handle differing perspectives?	Spatial variation is high and difficult to represent in carbon models – interpolating data from measured points is simple but generally inaccurate at meaningful management scales. Error/variability may or may not be included in downstream discussion.	The work was done primarily by an outsider, western academic trained researcher, who, even in collaboration with and working under Indigenous decision-making authority, has to be aware of the potential differences in problem framing. Here there was alignment in problem framing, but the potential for differences arose from how different conclusions could possibly be drawn from the qualitative material used in model construction.
Project planning: justice in design and outcomes.	Ensuring that stakeholder perspectives are credibly and accurately represented in a scientific model remains a challenge		While the project methods were clear, the overall research project lacked a theory of change.	Equifinality – choice of the model to represent the systems How will the modelling be updated and corrected as more is learned? Once a group is committed to a particular model and its results, it's harder to foster open-minded critical reflexivity and engage with critical peer review in good faith.		Ensuring decolonising methodologies and co-production approaches guide project planning, design and desired outcomes goes a long way to embedding just approaches throughout the research. Regarding the particular components of the model and their connections, validation is required by Indigenous knowledge holders.

Ethical engagement	How to resolve tensions between community needs, policymaker priorities, and expert opinions in the model? Not all stakeholders could be involved in the validation and testing of the model		Stakeholders – experts belonging to academia, government, industry and business actors, NGOs and umbrella organisations – had limited time availability and were interviewed individually. The modelling process did not create a space for discussion and confrontation among stakeholders.	Who is involved in undertaking the modelling, and whose knowledge is considered relevant?		Ensuring decolonising methodologies and co-production approaches guide project planning, design and desired outcomes goes a long way to embedding just approaches throughout the research.
Model development	Representing stakeholder perspectives in a multi-stage, multi-level model development process with different types of stakeholders Model complexity meant not all stakeholders could be involved in validation and testing stages	Were all the relevant experiences and knowledge captured? Did the choices made by the modeller inadvertently misrepresent processes or exclude people? Fear of getting things wrong in model design.		What to include or not include (what is in/out scope)? What kind of model is appropriate to represent the system of interest? Confronting models with data and confirming dynamics is made more difficult in nonlinear systems (e.g. to confirm chaotic dynamics you need to compare chaotic attractors rather than comparing exact time course of trajectories). Models are open systems and so can be tweaked and adjusted to be consistent with data, leading to a trade-off between parsimony and realism.	Complex models are largely limited to net movements of carbon through systems due to methodological constraints; the decisions on what inputs to include (and where to source the data from) have meaningful impacts on the modelled outcomes. Soil biogeochemical models will often contain several 'best educated guess' constants that may generate significant mathematical leverage on the modelled	Human centric (within a social-ecological system framing). Issues and potential risks regarding whose knowledges contribute to defining the 'system' (and representations of the drivers, determinants and their relationships) were a key aspect the broader research methodology addressed, but also need to be applied throughout the model development.

					movement of material through the system.	
Justice in information and resources		Was sensitive information such as poverty and inequality experiences represented respectfully and carefully?	Data was collected from international databases, however some countries had greater data availability than others.	Even observations are problematic: observations are theory-laden.	Model outputs (e.g., information about land) can be used by other parties in ways that could cause harm. For example, a bank may assign a risk profile to a lender based on model results volunteered for other purposes.	This is a central concern and reasoning behind choice of methods, though there is always room for improvement on reflection and with experience. For example, specific workshops to validate these models, could have been valuable in addition to a single collaborator perspective. Though models were built from ethically grounded qualitative material, there were limited opportunities for face-to-face discussions to validate findings at depth with diverse contributors (e.g. both men and women).
Characterise uncertainties and limitations			Agency (who is responsible for influence and change) was not included in the model or considered as part of reporting results, limiting its effectiveness.	A consequence of equifinality is that models can only be confirmed, not validated.	The purposes for which these models are used, such as in national carbon accounts and to monitor economic incentives to meet policy directives, largely omit uncertainty identified by the modeller. Assumptions on behaviour of carbon once incorporated into soil may not match actual biophysical process.	Limited opportunity to discuss and evolve models with collaborators and participants. Occurred at the end of research process, after analysis and field work. Ideally model would be iteratively discussed and refined, with more than one opportunity for discussion to review/understand how knowledge holders perceived uncertainties and assumptions made.

Evaluating outcomes			Model was validated through individual interviews with stakeholders. Discussion in a group setting may have had different results. Omission of agency (responsibility) from the model limits what the model results can be used for.	Induction/extrapolation issues (e.g., model confirmation against historical dataset doesn't mean it will hold when projected forward or used to extrapolate beyond the calibration context). How to interpret model results and evaluate their reliability?		No quantitative analysis of this. Final 'checking back' discussions required.
Clear communication			Communication with stakeholders has been clear. Equally, projects outcomes were communicated and shared, however, due to a lack of clear theory of change, the impacts of the project and its outcomes remained limited.	If model developers are explicit about model uncertainties or limitations, sometimes it means their modelling will be viewed less favourably than models developed by modellers who do not communicate limitations of their model.	Even with clear communication, the results of these models can still be used for purposes which may not adequately represent processes at a scale different from the modelled scale, or which do not take into account uncertainty and assumptions	While there was much work to communicate overall research findings in culturally appropriate and tailored ways, the conceptual modelling would have benefitted from more opportunity to discuss these models with knowledge holders.
Model repurposing				What happens if the modelling is taken and used in a different context outside the purposes for which it was designed?		
Organisational positionality and responsibilities		Modeller's contract ended before final results were provided back to stakeholders –	Stakeholders' engagement was also limited by scarcity of funding and other resources.	'Projectification' – once a project is finished there are barriers to revisiting the work, making corrections, updating in the light of new knowledge.	Institutions often don't question ethical aspects of these models/ institutional preferences for scientific inputs	Institutional ethical approval or other institutional processes likely ensure research ends or changes course if the skillset to

		whose responsibility is it to wrap up the project and not lose trust with stakeholders?			because they are seen as inherently credible.	navigate cross-cultural research is inadequate. Do institutions adequately allow for the time, resourcing and flexible planning needed working in these contexts?
Fostering ethical modelling practice and culture for modellers						Fostering ethical research practices is a central and ongoing focus in the disciplinary literature used.

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