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Evaluating Participatory Modeling Methods for Co-creating Pathways to Sustainability

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Key Points:

- Despite efforts to promote stakeholder engagement in modeling for sustainability, the ideal modes of participation remain uncertain
- We systematically evaluate and inform participatory modeling method selection for developing pathways to sustainability
- The results help the design of fit-for-purpose methodologies that best serve specific sustainability contexts of case studies

Supporting Information:

- Supporting Information S1

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Abstract The achievement of global sustainability agendas, such as the Sustainable Development Goals, relies on transformational change across society, economy, and environment that are co-created in a transdisciplinary exercise by all stakeholders. Within this context, environmental and societal change is increasingly understood and represented via participatory modeling for genuine engagement with multiple collaborators in the modeling process. Despite the diversity of participatory modeling methods to promote engagement and co-creation, it remains uncertain what the extent and modes of participation are in different contexts, and how to select the suitable methods to use in a given situation. Based on a review of available methods and specification of potential contextual requirements, we propose a unifying framework to guide how collaborators of different backgrounds can work together and evaluate the suitability of participatory modeling methods for co-creating sustainability pathways. The evaluation of method suitability promises the integration of concepts and approaches necessary to address the complexities of problems at hand while ensuring robust methodologies based on well-tested evidence and negotiated among participants. Using two illustrative case studies, we demonstrate how to explore and evaluate the choice of methods for participatory modeling in varying contexts. The insights gained can inform creative participatory approaches to pathway development through tailored combinations of methods that best serve the specific sustainability context of particular case studies.

1. Introduction

Ambitious and pressing sustainability aspirations such as the UN Sustainable Development Goals (SDGs) (UN, 2015) require rapid and sustained transformational change over time—termed *pathways*—across local, national, and regional scales (Gao & Bryan, 2017; Moallemi, Malekpour, et al., 2020). Traditional disciplinary approaches are inadequate for developing pathways in complex societal, economic, and environmental systems that have multiple stakeholders with different needs, values, and interests (Messerli et al., 2019). Practical research projects and science funding agencies suggest that researchers and stakeholders (i.e., local community, decision-maker, and business) should work together to *co-create* pathways for making progress in this complex space (Mauser et al., 2013). Co-creation—also closely related to other similar concepts such as co-design (Moser, 2016), co-production (Norström et al., 2020), transdisciplinary collaboration (Michas et al., 2020), and postnormal science (Funtowicz & Ravetz, 1993)—aims to integrate science and policy and bridges divides between disciplines in developing viable pathways to address complex sustainability challenges (Messerli et al., 2019; Norström et al., 2020). Co-creation also nurtures creative thinking by navigating different views among stakeholders and suggesting solutions that are contextualized for the problems at hand.

Co-creation in sustainability research has been increasingly attained through the integration of modeling with genuine stakeholder engagement that is often framed as *participatory modeling* (Voinov et al., 2018) or

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participatory multimodeling (Cuppen et al., 2020), in which modelers and stakeholders collaborate in support of a shared understanding of systems for sustainability transformations. A diversity of methods have been suggested in the literature for participatory modeling (Halbe et al., 2020). Despite increasing efforts to promote participation through these available methods (Voinov et al., 2018) and efforts to understand design choices in participatory modeling (Cuppen et al., 2020), it remains uncertain in practice what the amount and modes of participation are under different conditions, and how to select the suitable methods for a given situation (Glynn et al., 2018). This uncertainty becomes even more challenging in sustainability pathway analysis which often comprises multiple steps (e.g., generating scenarios and evaluating strategies), requiring researchers to use various methods under a different set of requirements (e.g., data availability, problem complexity, and stakeholder interest). Myriad analytical methods with different requirements across the various steps of pathway analysis create a methodological dilemma in transdisciplinary research projects (Harrison et al., 2018). A related survey that we conducted at the beginning of this study showed that researchers have different views on how and when stakeholders should be engaged in pathway development (S1 in supporting information). A major source of this disagreement is rooted in biases toward past experience and disciplinary conventions (Glynn et al., 2017). These biases in practice can often lead to a premature selection of methods that may overlook other potential alternatives for stakeholder engagement (Moallemi, Zare, et al., 2020). The challenges in method selection can be further amplified by other practical barriers such as the lack of willingness to collaborate among researchers from different backgrounds and to interact with stakeholders; potential conflict of interest among stakeholder cohorts; and stakeholder fatigue due to overconsultation (Smajgl & Ward, 2015).

Here we propose a unifying framework to evaluate and inform method selection and to judiciously engage stakeholders in modeling for pathway development. The framework enables researchers to be transparent and systematic in exploring the choice of methods. To develop the framework, we explore the suitability of different participatory modeling methods and analyze their integration in practice. We start by identifying available method capabilities from the review of a wide range of qualitative and quantitative methods in sustainability research with different levels of stakeholder participation. This will be followed up by the identification of potential requirements that could influence the choice of method for co-creating pathways across various contexts, such as working with stakeholders with no prior exposure to strategic consultation. We combine an extensive literature search with expert elicitation to identify these potential requirements. We then undertake a systematic assessment to analyze the suitability of methods for meeting these requirements in different sustainability contexts and for iterative steps of pathway analysis.

The rest of the article is structured as follows. We introduce the proposed framework for evaluating the suitability of methods in Section 2. We then apply the framework to two case studies in Section 3. We discuss the potential implications and remaining challenges of using the proposed framework in Section 4. We explain the theoretical background and details of the proposed framework in Section 5, containing all elements necessary to allow the implementation of the framework in other studies and replication of the results. Further details are also provided in the supporting information and Code and Data Availability.

2. A General Framework to Assess Method Suitability

We developed a simple yet systematic framework for evaluating method suitability in co-creating pathways to sustainability (see details in Section 5). At the highest level, the framework evaluates suitability based on how available participatory modeling methods can address the practical requirements of a given situation (Figure 1). To explain how the framework helps select suitable methods, we need to: (1) identify method options for participatory modeling that offer different capabilities; (2) specify potential practical requirements that can impact method selection; and (3) assess method options against the practical requirements (i.e., method suitability) to identify those method(s) that are likely to perform better. Below we discuss these three steps of the framework.

2.1. Identifying Method Capabilities in Participatory Modeling

Drawing on a multidisciplinary literature review (see Section 5.1), we identified a total of 43 methods which offer different yet sometimes overlapping capabilities for developing sustainability pathways. To understand

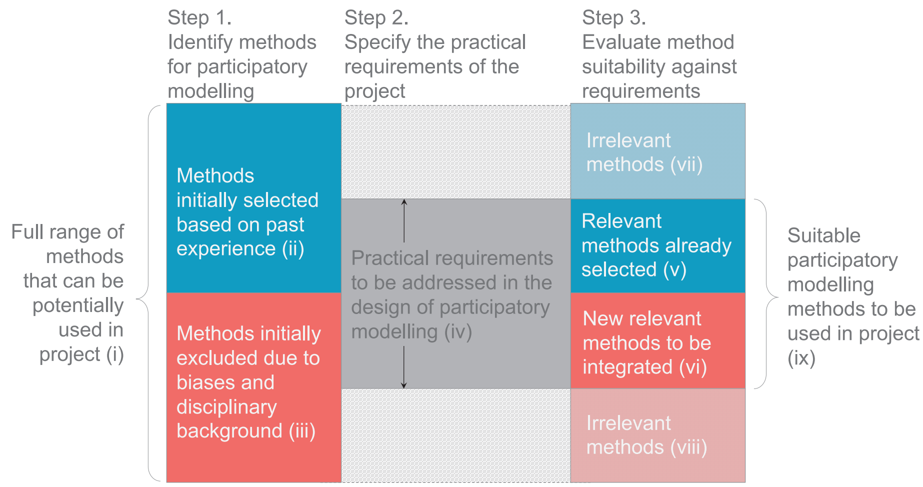

Figure 1. The framework for assessing the suitability of participatory modeling methods (see Sections 5.4 and 5.5 for details). In Step 1, we identify a wide range of available methods which include various qualitative and quantitative participatory modeling techniques for pathway analysis (i). Some of this maximum range of methods are initially considered to be important, biased by past experience and hidden motives of researchers (ii), and some others (e.g., from other disciplines) are likely to be missed as they belong to other domains or as researchers are not confident in using them (iii). In Step 2, we specify certain requirements of the specific project for the co-creation of pathways (iv). These requirements guide what aspects (e.g., high vs. low uncertainty conditions) the methods should be capable to address in pathway analysis. In Step 3, we assess the full range of method options against the practical requirements to identify the suitable methods for participatory modeling that can sufficiently address project's requirements (ix). Some of these suitable methods were already likely to be included by researchers in the participatory modeling design (v). However, some others were not initially considered important, but the assessment of methods against project's requirements identified them as relevant techniques that should be integrated in the design of participatory modeling. From the full list of initial methods, there are also some irrelevant techniques (vii, viii) that do not address any particular project's requirements and are not needed in the design of participatory modeling. The conceptual representation of the framework is inspired by Chaplin-Kramer et al. (2019).

these capabilities, we compared: (1) the type of problems that they can address, (2) the way they can be implemented, (3) the level of formalization (i.e., the ability to consolidate input assumptions into a formal structure), and (4) the level of stakeholder participation. A full comparison of the reviewed methods is available in S4 (supporting information). Here we only present an overview of these methods in two dimensions (Figure 2): the level of participation and the level of formalization.

Across the first dimension, at limited to moderate levels of participation, methods are often used to engage with stakeholders to extract necessary knowledge for informing the pathway development process. For example, a method such as cost-benefit analysis obtains stakeholder preferences to incorporate into the evaluation of competing solutions, but the analysis itself is performed independently from stakeholders. However, at moderate to intensive levels of participation, methods are performed with stakeholders in a process of genuine engagement and co-learning. For example, role-playing games are centered around stakeholder engagement to create a shared understanding about solutions to a common problem (Lonsdale et al., 2008).

In the second dimension, depending on the level of formalization, methods can be qualitative or quantitative. Qualitative methods rely mostly on conceptualization and assumptions about scenarios, actions, and the way the system works. A quantitative method, however, has the ability to consolidate input assumptions into a symbolic, formalized language for greater clarity and analytical rigor. Anything in between is considered semi-quantitative; for example, where some qualitative data (e.g., human values and preferences) are processed using a quantitative technique (e.g., fuzzy cognitive mapping), or a set of numerical values (e.g., survey) is analyzed using standard calculations (e.g., weighted average). As the degree of quantification and formalization of assumptions in method implementation increases, the ability to reproduce system behavior and therefore to scientifically validate results improves. On the other hand, relying on quantitative information may lead to diminished cultural and cognitive richness of the information compared to qualitative assessment.

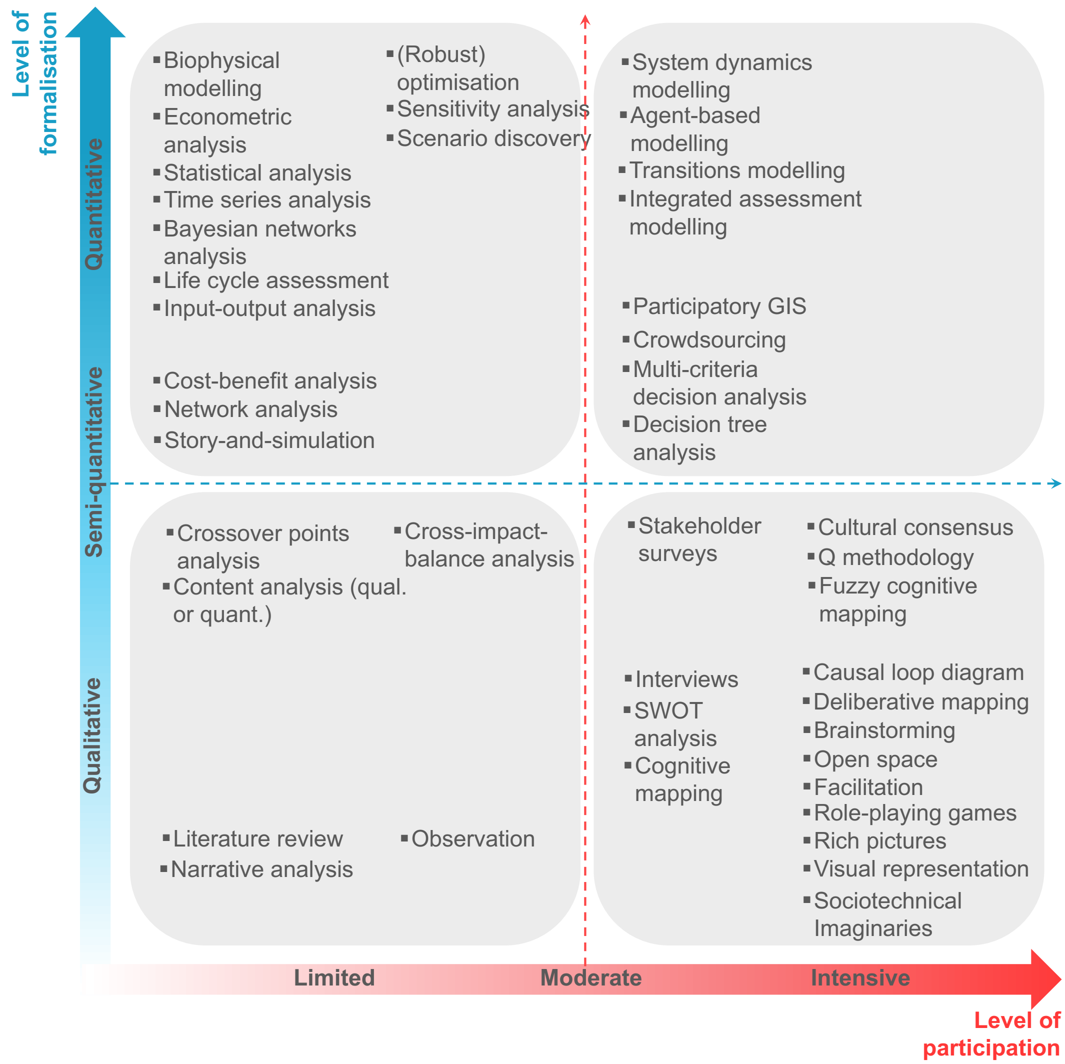

Figure 2. Identified participatory modeling methods for co-creating pathways toward sustainability goals with stakeholders. The methods vary in two dimensions: level of participation (x-axis) and level of formalization (y-axis). A method can be more qualitative or quantitative (or equally more or less participatory). The distinction between quantitative and qualitative methods and limited and intensive participatory methods is not always clear-cut. Methods that are arranged within the quadrants close to the middle horizontal line are more mixed qualitative-quantitative compared to those that are further away. Methods that are arranged within the quadrants close to the middle vertical line are moderate participatory compared to those that are further away. See the definition and comparison of all methods in S4 (supporting information).

These two dimensions create four general quadrants of participatory modeling methods with different capabilities that can be used for co-creating sustainability pathways. As shown in Figure 2, the top-left quadrant includes techniques for developing computational models and analyzing modeling results. Some of these techniques (e.g., scenario discovery [Bryant & Lempert, 2010]) are supported by participatory processes while others (e.g., econometric analysis and network analysis) use available knowledge and are rarely considered as participatory. The top-right quadrant includes quantitative techniques (e.g., mathematical and computer models) to facilitate stakeholder participation for the acquisition of knowledge in decision-making (e.g., decision tree analysis [Sieber et al., 2018]) or for creating supportive or counterfactual insights to inform human judgment of complex interactions (e.g., system dynamics modeling [Sterman, 2000]). The bottom-right quadrant includes techniques for obtaining knowledge from stakeholders (e.g., interview and survey), communicating it between different groups (e.g., facilitation), and processing it (either qualitatively or semi-quantitatively) with stakeholders to reach a common understanding (e.g., sociotechnical

Figure 3. Practical requirements that can influence the choice of methods in co-creating sustainability pathways with stakeholders. The requirements are grouped into three categories: outcome-oriented, research-oriented, and stakeholder-oriented. In each category, the first column is the name of the category, the second column is the name of the subcategory, and the third column is the requirements. See S5 in supporting information for further details.

imaginaries [Jasanoff & Kim, 2015], causal loop diagrams [Sedlacko et al., 2014]). The bottom-left quadrant includes techniques suitable for collecting and analyzing information (e.g., literature review, content analysis), rather than relying on self-reported information through participatory methods (e.g., surveys). They also include techniques supported by a limited numerical analysis of semi-qualitative information (e.g., weights, ranking, values) for identifying relationships among various factors (e.g., cross-impact-balance analysis [David & Bernard, 2019]).

2.2. Specifying Practical Requirements of Methods for Co-creating Pathways

The choice of method for co-creating pathways can be influenced by several requirements in practice. Through a literature review (see Section 5.1), we identified 27 different requirements. As shown in Figure 3, the list of practical requirements was summarized in three primary categories: outcome-oriented, research-oriented, and stakeholder-oriented (each with multiple subcategories). The full description of these requirements is available in S5 (supporting information).

The *outcome-oriented* requirements are those related to the analytical objective in pathway development. For example, when researchers focus on agenda setting and drawing a long-term vision, they often rely on participatory methods (e.g., facilitation) to align the downscaling of global sustainability goals with the specific priorities of their stakeholders and to create a shared understanding of a picture of what a successful future looks like (Kunseler et al., 2015). However, when researchers are exploring scenarios, they may be better off with computational methods (e.g., scenario discovery [Lamontagne et al., 2018]) that can comprehensively search the uncertainty space and enumerate plausible scenarios. The outcome-oriented requirements are also related to the type of results expected in a case study. For example, a case study in the context of health and well-being needs to evaluate several qualitative indicators (e.g., community happiness). This would require qualitative and participatory methods that are capable of evaluating unquantifiable variables rather than calculating their poorly correlated, quantified equivalent (e.g., the health insurance coverage for measuring a healthy lifestyle). However, a case in the context of energy needs the evaluation of quantitative indicators (e.g., energy demand and production). This would require different types of methods that are capable of generating numerical projections for relevant outcomes.

Research-oriented requirements are related to the scientific rigor of methods to cope with the problem and the availability of resources such as data and expertize for method implementation. For example, a case study with a limited (i.e., deterministic or well-characterized) uncertainty can make good use of a method such as time series analysis (Khazaei et al., 2019; Papacharalampous et al., 2020) for future projection, whereas another case study with high (deep [Lempert et al., 2003]) uncertainty would require methods that are better capable of exploring unknown futures, such as robustness techniques (Herman et al., 2020).

The *stakeholder-oriented* requirements are related to stakeholder characteristics in method implementation. For example, the limited strategic thinking maturity of a case study diminishes the opportunities for human creative thinking about problem cause-and-effect. This can make a method that relies solely on stakeholder insights less suitable compared to methods that can complement these insights with available knowledge of best practices from the literature. Here, a stakeholder is defined as anyone involved in sustainability practice at different levels of influence. This can include decision-makers, local experts, clients, advocacy groups, power groups, and communities.

The practical requirements of these three categories can vary across projects based on their *context* (e.g., sustainable agriculture in a regional area vs. climate mitigation) and the *steps* of their research process (e.g., discovering future scenarios, assessing vulnerabilities). Specifying the practical requirements of the project's context is important since case studies are not homogenous and have various characteristics, requiring different methods. Imagine a context such as housing development in a small town where there can be a high-level of confidence in stakeholders' predictions of the future's supply and demand. Here, coping with high uncertainty is not an important requirement in selecting methods for developing pathway toward affordable housing. Conversely, a context such as biodiversity loss where the people's knowledge of human-natural system interactions is limited requires methods that can effectively investigate system complexities and future uncertainties.

Specifying the practical requirements of the project's steps is important too. The co-creation of pathways typically involves several steps (Haasnoot et al., 2019), such as envisioning a desired future and evaluating the performance of actions for achieving the vision, where a different set of method capabilities are required for each step (see Figure 7 in Section 5.2 and Table S1 in supporting information for the steps' overview). For example, action evaluation is a step that requires the assessment of numerous nonlinear interactions that can affect system performance. This may need more computational methods capable of dealing with high problem complexity and the analytical power to examine feedback loops between possible causes and consequences of a given problem. However, the same requirement might not be equally important in selecting methods for envisioning desired futures. Envisioning is a collaborative step aiming to reach a common understanding about what the success means; therefore, it prioritizes methods that can shape a legitimate normative direction with consensus among stakeholders' divergent values. Given this variation in the contexts and steps in pathway development, a specific subset of requirements will always become more important than others in each participatory modeling practice. This makes some methods which possess the required capabilities more suitable than others at each step and necessitates a combination of methods to meet the diversity of requirements in the life of a pathway development project.

2.3. Assessing Method General Suitability

To assess general suitability, we analyzed the extent to which a method's capabilities can address the practical requirements. By general suitability, we mean the strengths and limitations of methods independent from any case studies. For example, a method such as robust optimization (Gold et al., 2019) that can help in making effective trade-offs between multiple conflicting objectives is suitable for conditions with stakeholder disagreement about priorities and trade-offs between sustainability goals. We assessed general suitability in a process where a group of researchers from natural, physical, and social sciences shared their expertize and negotiated the extent to which methods can address the requirements in a workshop and a follow-up survey (see Section 5.4; S1 in supporting information). The outcome, which was a negotiated assessment of method suitability among the participating researchers, was represented in a heatmap (Figure 4) to inform specific case studies in two ways: (a) enabling the selection of methods in practice under "what-if" scenarios (i.e., "what" methods would be suitable "if" a case study is characterized by particular requirements); (b) highlighting the opportunities for integration among different methods in practice (i.e., what method capabilities would be complementary for a given case study). We discuss (a) and (b) in two case-specific examples in Section 3.

3. How to Use the Framework in Practice

The framework for the assessment of method suitability can be customized to the specific requirements of the case, meaning that researchers choose a mix of methods with capabilities that can effectively address the problem at hand. Potential users can apply this framework via three simple steps (see Section 5.5): (1) select a subset of practical requirements (from the list provided in Figure 3) that are most relevant to the case study; (2) evaluate and select which subset of method capabilities (from the general assessment in Figure 4) could meet case study requirements at the beginning of project; (3) re-evaluate and adjust the methods selected initially over the course of the case study project. We used two different examples from pathway development in southern Australia, that is, the Goulburn Murray and the Forrest/Otways regions, to demonstrate how the three methodological steps are implemented. Our aim in both examples was to use the framework for an evaluation of methods at the onset of project to identify suitable participatory modeling approaches for pathway development in each region.

3.1. A Brief Introduction to the Two Case Studies

We studied two local regional case studies in Victoria, Australia. They are two cases of interest for testing our framework as they have two different sustainability agendas (focused on sustainable agriculture [SDG2] and health and wellbeing [SDG3] respectively), and as they represent two different sets of contextual characteristics (e.g., type of results expected, resources, stakeholder availability). In both cases, the aim was to develop robust pathways toward future-proofing local communities that will enable people and nature to thrive in the future. The first case is the Goulburn Murray region. Located in north-central Victoria and known as the "food bowl of Australia," this study area is a vast agricultural region far from the coast and heavily reliant on the Murray Darling Basin for the livelihood of local communities and ecosystems as well as for agricultural irrigation. This case study focuses on the environmental and economic pressures facing the irrigation, dairy, and food production industries. The second case is the Forrest/Otways region, located in south-west Victoria, in an area with unique rainforest ecosystems, highly susceptible to the environmental and socio-economic effects of climate change. The Forrest/Otways region involves a small community, in transition from agriculture and logging industry to eco-tourism, that is striving to attain a sustainable and resilient future in the midst of increasing fire threats and water shortages.

3.2. Specifying Case Study Requirements for Co-creating Pathways

To understand the characteristics of the problem at hand for selecting the right methods, we specified the requirements of each case study based on their specific contexts and steps in pathway development. We gave each general requirement in Figure 4 a score to represent its importance for method selection in each case. Scores were based on our assessment of available knowledge (e.g., what data exists, what expertize the research team has) and feedback from local experts (e.g., how uncertain the problem is, how engaged the stakeholders are) obtained through meetings and workshops (see Section 5.5). Figure 5 shows the importance score of the requirements in the two contexts and across the steps in the pathway development process.

Specification of case-specific requirements showed that requirements can differ in importance between case studies. The cases had different contexts characterized by various sustainability priorities,

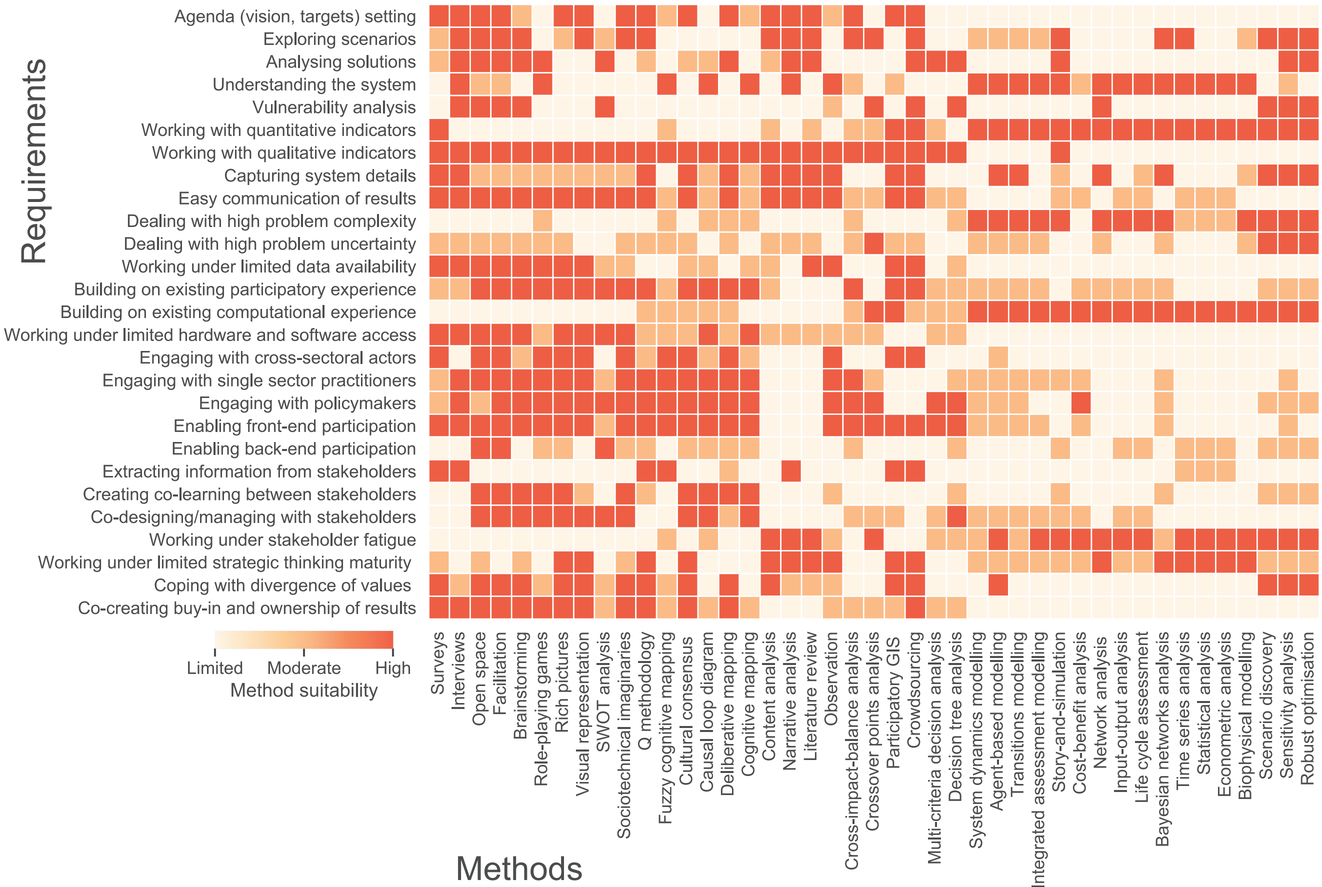

Figure 4. The general suitability of methods. The suitability is estimated based on scores assigned by researchers from different natural and social science backgrounds (see Section 5.4). The intensity of colors shows the degree of suitability: limited, moderate, and high. The higher the color intensity, the more suitable the method in a case study, with that requirement. The methods (x-axis) are ordered based on the four quadrants of Figure 2 from bottom-right, to bottom-left, to top-right, and to top-left. The requirements (y-axis) are ordered based on their categories, from outcome-oriented, to research-oriented, to stakeholder-oriented.

engagement fatigue, and documented information availability. The Goulburn Murray region has been long subjected to strategic planning and intensive engagement activities aimed at promoting sustainable agriculture among other sustainability goals (MDBA, 2018). This long planning history has helped in shaping a shared perspective about the future of the agricultural sector among stakeholders through multiple consultation processes. It has, however, resulted in significant stakeholder fatigue and reluctance among stakeholders for new engagement activities. This long consultation history has also created a rich source of data, models, and knowledge of agriculture, land, water, and the economy. Conversely, the Forrest/Otways region is a small, tourism- and service-focused community that aims to achieve multiple sustainability goals including health and wellbeing of different generations in the town (Szetey et al., 2020b). The context of this case is characterized by limited data and models of local environmental, social, and economic conditions. However, community members are passionate about engaging with researchers to share their local knowledge and co-design effective solutions. We present here only an overview of the two cases for illustration. More details about how the context information was interpreted as requirements are available in Section 5.5.

In addition, the specification of case-specific requirements showed that the importance of practical requirements varied among the steps of the pathway development process. We evaluated method suitability through the multiple steps originally framed by Haasnoot et al. (2013) (Figure 7). They start with visioning and target setting where a long-term desirable future with measurable goals and targets is defined. Then the

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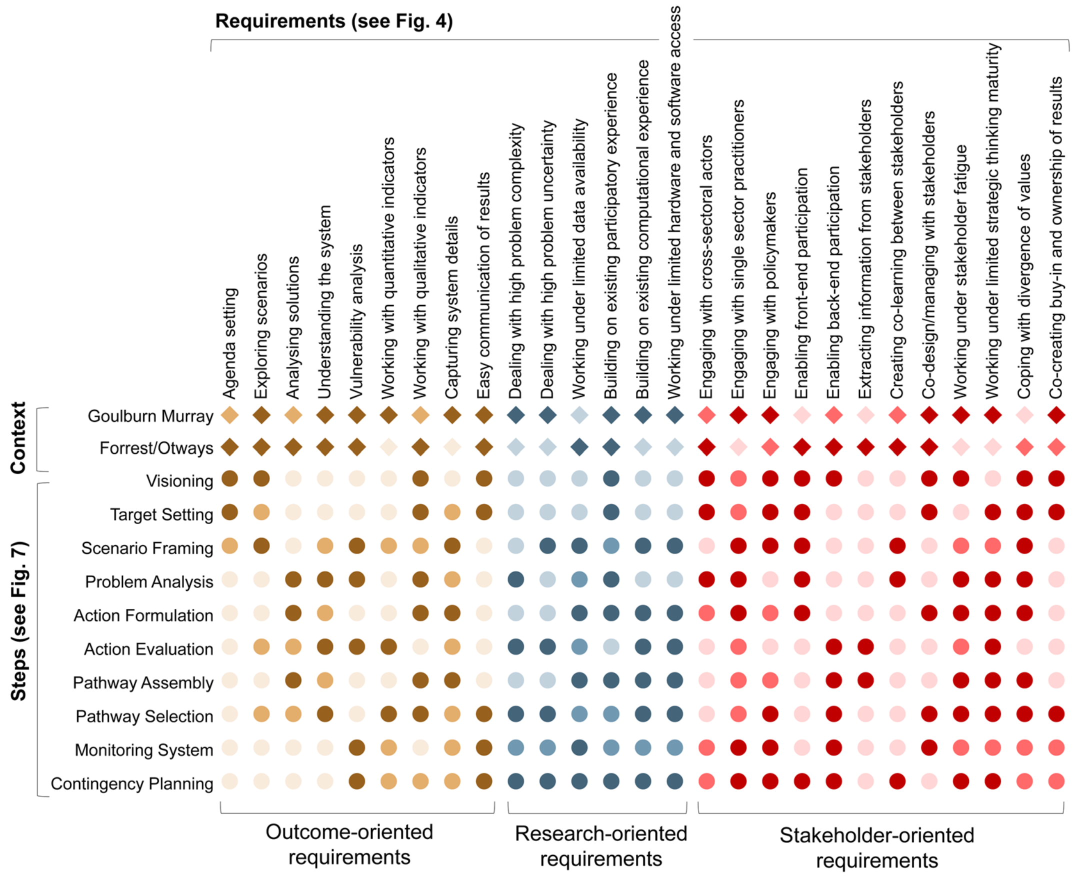

Figure 5. The specification of the practical requirements in the case studies. The intensity of colors shows the importance (low, medium, and high), which varies depending on the context. For example, in Goulburn Murray, there have been several visioning exercises in the past whereas Forrest/Otways is fairly new to long-term strategic thinking. Therefore, "agenda setting" has a lower priority in Goulburn Murray than in Forrest/Otways. The importance of the requirements also varies across the pathway development process in the case studies. For example, "creating buy-in and ownership of results" is a more important requirement in the early and final steps of pathway development where it is crucial that stakeholders agree on and own the desired vision (e.g., visioning) and the ways to achieve it (e.g., pathway selection), for successful implementation. The importance of the requirements is estimated by the authors, informed by experts' feedback and literature (see Section 5.5).

future scenarios that can impact the achievement of the targets are explored (i.e., scenario framing). Given challenges and opportunities, a set of short- and long-term actions are formulated, and their effectiveness in achieving the targets is analyzed (i.e., problem analysis, action formulation, action evaluation). The sequence of actions together creates pathways toward long-term goals (i.e., pathway assembly and pathway selection). The pathways are dynamic and adaptive meaning that options remain open for future adjustment as the change of condition is identified through monitoring (i.e., monitoring system, contingency planning). The description of these steps in the pathway development process is available in Section 5.2 and in S2 (supporting information). Each of these steps, depending on their aim and expected outcomes in pathway development, requires a different set of method capabilities. For example, we gave a high score to the importance of engagement with cross-sectoral actors in a step such as visioning with an aim to draw a successful future agreed by all. Strong engagement helps capture the diversity of views and perspectives among stakeholders. Conversely, in action evaluation, we scored highly the ability to cope with the complexity of the system and potential trade-offs, synergies, and side-effects. Action evaluation aimed to analyze the effectiveness of specific solutions over time and place, and therefore needed methods that can account for the complexity. More details about how the steps in pathway development were linked to practical requirements are available in Section 5.

3.3. Evaluating Method Suitability in Case Studies

We explored and evaluated the suitability of methods in the two case studies by measuring the gap between the requirements of each case (Figure 5) and what the methods can offer (Figure 4). The smaller the gap, the more suitable the method (see Section 5.5). The results are represented in a heatmap in Figure 6. As a general overview, the case-specific assessment showed that suitable participatory modeling methods with different levels of engagement with stakeholders varied significantly between the two cases. While the role of stakeholder engagement through highly participatory and qualitative methods was identified as significant in the Forrest/Otways region, less participatory and more quantitative methods played a crucial role in the Goulburn Murray region. This methodological variation was attributed to differences between the case studies in their sustainability (qualitative vs. quantitative) indicators, model fidelity and the availability of datasets, and stakeholder eagerness to engage.

To give more detailed insights, the results showed that developing pathways in the socio-ecological contexts of each case study required more than the simple methods suggested by disciplinary approaches. Concepts and solutions from a range of natural and social sciences needed to be integrated in each case (Roux et al., 2010). For example, in Goulburn Murray, a set of contextual characteristics, such as priority for quantitative agricultural production indicators, availability of models and data sets, and stakeholder reluctance for engagement, made modeling methods rather than participatory approaches, more suitable for pathway development. More specifically, modeling approaches such as integrated assessment modeling (Hamilton et al., 2015) and transitions modeling (Köhler et al., 2018), in conjunction with computational techniques such as sensitivity analysis and scenario discovery (Bryant & Lempert, 2010) were among the most suitable methods for this case. These methods were deemed useful in Goulburn Murray given their capability in the point-by-point identification of specific land-use management actions, their related geographies across spatio-temporal scales, and their ability to quantitatively analyze transformative change in food and agricultural systems.

The outcome for this case, however, limited the use of participatory and qualitative methods to a supporting role for model development and analysis. For example, methods such as cultural consensus (Ulrich et al., 2016) and cognitive mapping (Nasirzadeh et al., 2020) were among suitable methods because they could be used to elicit stakeholder inputs to inform the model development process and to create consensus about the boundary of problems to analyze, especially at the early stages of the project. Other participatory and qualitative methods, such as causal loop diagram (Zare et al., 2017), were also regarded as suitable because of their capability in capturing the diversity of stakeholder views to the changing dynamics of the system, which could help in modeling system feedback interactions.

The suitability of methods was, however, different in the case of Forrest/Otways. Participatory and qualitative methods were identified among highly suitable techniques. This result was driven by a different set of contextual characteristics, such as the priority for evaluating qualitative rather than quantitative targets (e.g., well-being), limited information about what the future can look like, and the community's willingness to engage. More specifically, methods such as open space (Martin et al., 2018) and sociotechnical imaginaries (Jasanoff & Kim, 2015) were among the most suitable methods as they could help in exploring the future through visioning, downscaling global goals to local priorities, and constructing scenarios with local communities. The high diversity of views among stakeholders also made methods such as role-playing games (d'Aquino & Bah, 2013) and SWOT analysis (Arbolino et al., 2018) suitable for confronting opposing ideas and maintaining a diversity of views on problematic situations and their effective solutions.

The results also showed that suitable methods could vary in the pathway development process driven by the diversity of outcomes expected from each step. In the case of Goulburn Murray, visioning and target setting were identified as two steps that relied on highly participatory and qualitative methods. Such methods (e.g., brainstorming and cognitive mapping) were considered to be better able to incorporate the viewpoints of different stakeholder groups and shaping a shared, socially robust understanding of what was to be achieved, which were both important in visioning and target setting. However, different types of methods were identified as suitable for steps such as scenario framing, action evaluation, and pathway assembly. Here, quantitative methods with limited participation were considered to be more useful. For example, exploratory modeling techniques (Moallemi, Kwakkel, et al., 2020) such as sensitivity analysis (Lamontagne

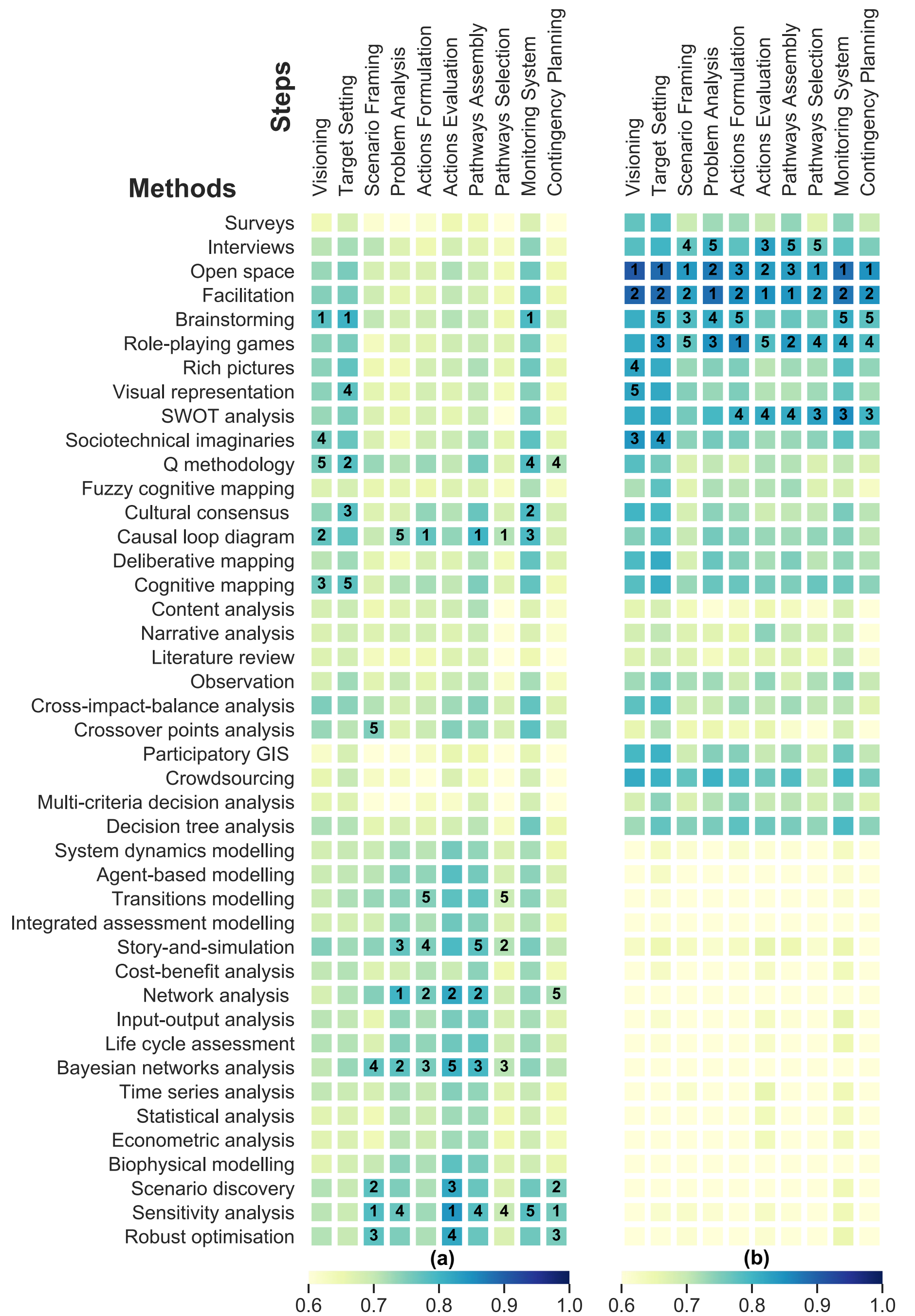

Figure 6. The suitability of methods for co-creating sustainability pathways in two case studies: (a) Goulburn Murray; (b) Forrest/Otways. The rows in the heatmaps are methods. The columns are the steps in the pathway development process. The intensity of color represents method suitability in each step for each case. The numbers in the heatmap cells indicate the top five suitable methods for each case—that is, the methods with the five highest scores at each step. The methods (y-axis) are ordered based on the four quadrants of Figure 2. The operations underlying the ratings are explained as text and equation in Section 5.5.

et al., 2018) and scenario discovery (Hadjimichael et al., 2020) was suitable in scenario framing given that it could systematically scan the diversity of possible transient futures to identify key scenarios where pathways could succeed or fail to meet targets. Other modeling methods such as transitions modeling (Köhler et al., 2018) combined with computational approaches such as robust optimization (Gold et al., 2019) were identified as suitable in action evaluation and pathway assembly. They were thought to be helpful in

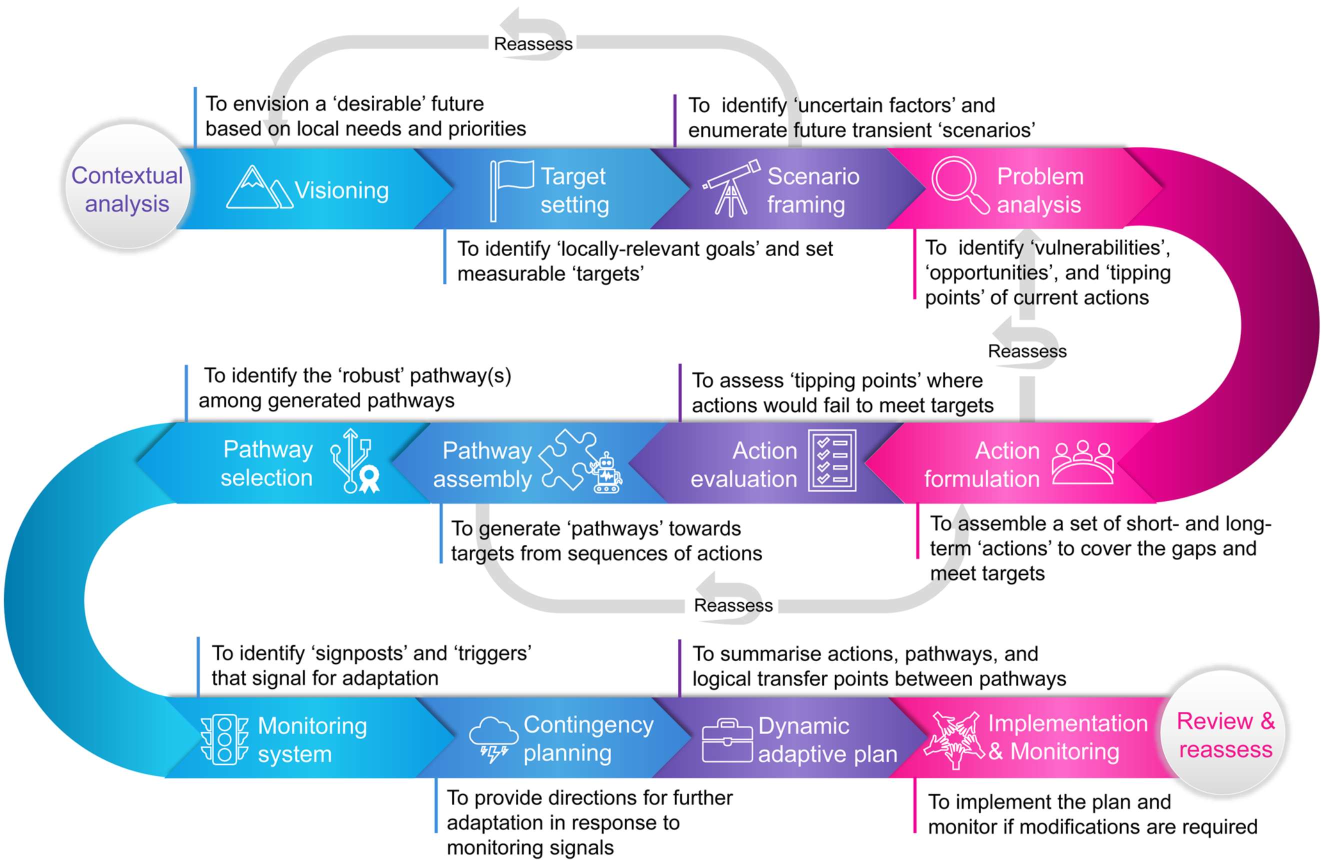

Figure 7. An overview of the steps in developing pathways toward sustainability goals. The process is iterated over time as the knowledge about the system and its context increases. Adapted and redesigned from Haasnoot et al. (2013) and Lawrence et al. (2019).

simulating and analyzing the efficacy of contested strategies proposed by various stakeholder groups over space and time. They were also useful in informing trade-offs between multiple (often conflicting) objectives that various stakeholders hold in the evaluation of actions and pathways. The variation of methods across the steps was also observed in the case of Forrest/Otways, but to a lesser extent and mostly in terms of variations from one group of highly participatory methods to another. For example, while methods such as open space, brainstorming, and facilitation were identified as suitable across all steps, some others (e.g., sociotechnical imaginaries) were useful only in few specific steps (e.g., visioning and target setting).

The assessment of method suitability in the two case studies was undertaken at the beginning of their respective pathway projects. Such *a priori* evaluation is regarded as a starting point, helping to acknowledge different perspectives in coping with complex transdisciplinary problems. *A priori* evaluation is intended to facilitate an effective flow of information and to enable transparent communications among researchers and stakeholders from extended scientific and expert communities involved. Hence, the assessment of method suitability should not be interpreted as the "only right" and "a fixed" way of designing participatory modeling processes. Rather, it should be regarded as a negotiated outcome among collaborating researchers and a changed practice based on current evidence, which could be subject to change over the course of the project (as we further discuss in Section 3.4).

3.4. Re-evaluating Method Suitability through Reflection

The evaluation of methods in the two cases was based on the available knowledge of each case study's requirements (from experts and documents as specified in Section 3.2) at the start of the pathway development project. Contexts and requirements, however, can vary over time due to irreducible uncertainties and the emergence of new information (Walker et al., 2013), and this can change the suitability of methods throughout a project. For example, travel restrictions, as a result of the global COVID-19 pandemic, have changed how researchers can interact with stakeholders and whether some of participatory approaches can still remain effective in their previous settings. There might be also initial knowledge gaps about available resources which can be improved over time, and therefore impact the methods that researchers will use in project's later stages. For example, initial misperceptions about good access to data and the high fidelity of available models at the start of a study can lead to the selection of more model-based rather than qualitative approaches. However, once the misperceptions are uncovered along the way, researchers may require adjusting their initially selected modeling methodologies to suit their currently available resources.

These and other similar changes necessitate *reflection* and *method re-evaluation* which will help assess whether the methods selected at the beginning of a project will continue to deliver the expected outcomes (Roux et al., 2010), or if other methods should be considered as new conditions emerge (Voinov & Bousquet, 2010). Reflection on and re-evaluation of participatory modeling methods in projects can also enhance cross-domain learning between participants of a collaborative exercise in long-term. They can help in addressing the expectations of participating researchers and maintain continuous engagements with users to design and execute the methodologies aligned with their needs. There is an extensive literature about reflection on theory and methods as well as how reflection should be used to inform the design of participatory modeling. Among them, Roux et al. (2010) and Zare et al. (2020) have proposed frameworks for co-reflecting on the accomplishment of transdisciplinary research which could be used along with our suggested framework to ensure rigor and build confidence in the assessment of method suitability during the project's lifecycle.

4. Implications and Challenges for the Pursuit of Sustainability

The insights from this research are important for designing fit-for-purpose methods for co-creating pathways with stakeholders in two ways. First, they inform creative engagement solutions through tailored combinations of methods that best serve specific sustainability contexts of the case studies and their desired outcomes. There is no "unique" or "best" combination of participatory and modeling methods for sustainability in practice, and there are often multiple methods that can address the same problems effectively but in different ways (Khatami et al., 2019). This is key to the implementation of global sustainability frameworks such as the SDGs which cover diverse domains such as food, energy, water, health, and biodiversity, and need multiple tools and techniques to address their various characteristics and requirements. Our proposed systematic framework in this paper offered both a method toolbox and an assessment of their available capabilities to help researchers in deciding which method(s) to use and when to use them in participatory modeling. Second, we expect this study to inform the effective integration of multiple techniques in a way that can help researchers complement the limitations of one method with the strengths of others. The selection and integration of methods in practice have often been biased by past experience and hidden motives of researchers, driven by the mantra "*when you have a hammer, everything looks like a nail*" (Glynn et al., 2017; Zare et al., 2020). Our proposed framework can assist in judiciously evaluating strengths and weaknesses of different methods and inform a suitable integration of various techniques for a given situation.

Despite our framework's contribution in systematically analyzing the overall needs of the project and then specifying suitable methods for stakeholder participation (i.e., scientific dimension of transdisciplinary collaboration), maintaining an actual collaboration throughout the research process will still face challenges in practice. One of these challenges is that realizing a balanced and broad coalition of relevant collaborators—who can represent a range of skills (e.g., data analysis, socio-behavioral dimensions) and types of knowledge (e.g., academic, indigenous, and experimental)—cannot be easily achieved within the practical and strategic limits of projects (Nel et al., 2016) and with reasonable facilitation costs (Harvey et al., 2019). Researchers of different disciplines with focus on various epistemological aspects (e.g., ecologists vs. economists vs. sociologist) and stakeholders with diverse needs and priorities (e.g., community members vs. decision makers vs. businesses) can find it difficult to get along and work together for implementing mixed methods. The power dynamics and power asymmetry among various collaborators (e.g., organization hierarchy and disciplinary dominance) is another challenge that can put the engagement quality at risk and undermine the value and usefulness of skills from other disciplines. Other practical challenges can also exist related to passive engagement (i.e., at the beginning or completion of project) where collaboration between actors remains limited to only the initial design or final validation of the project rather than continuous interaction from framing the research, to conducting and implementing it, and to jointly distributing the generated knowledge.

Solutions to address these challenges would be highly sensitive to the settings of each specific project, and there would be no universal approach that can work in every situation. However, past research has put forward some general principles and suggestions to mitigate these challenges by enhancing the recognition of different ways of doing and knowing and ensuring continuous engagement from a range of perspectives on a given issue throughout a project's lifetime. For example, a facilitated step-wize approach to participation, where collaborators with required expertize are involved at different points with different leading and supporting roles, can reduce potential conflicts of views and maintain a coalition of knowledge and expertize across disciplines (Norström et al., 2020). Such pluralistic processes can be guided and facilitated by individuals or teams with broad knowledge across disciplines and skills, sometimes referred to as boundary spanners (Bednarek et al., 2018) or knowledge brokers (Miller et al., 2014), to enrich learning and trust among collaborators and facilitate conflict resolution. The use of practical tools for identifying positions of power among collaborators can also be helpful in bringing an understanding of power relations in efforts to build, shift, or influence power asymmetries (Gaventa, 2006). This will foster equal contributions from various knowledge and practice domains. Finally, sharing experiences, ideas, and values through frequent and active interactions (e.g., workshops, meetings, and blogposts) and dialog between stakeholders and scientists are among other ways to promote the exchange and interaction of knowledge and facilitate learning and collective action among various collaborators to maintain scientific quality and societal relevance throughout a research process.

Our proposed framework for participatory modeling along with these general recommendations will contribute to the transdisciplinary understanding of sustainability problems at the interface of *knowledge* systems where academics operate, and the realm of *action* where policymakers and stakeholders sit. This is key to dealing with the complex challenges of coupled human-natural systems in a world where the co-creation of knowledge is greatly valued, and where policy agencies and science funding organizations increasingly encourage (if not mandate) co-creation and co-learning among scientists and stakeholders. We expect that such transdisciplinary interfaces can take advantage of the vast range of available methods to increase the chances of successful implementation in the context of high-impact global science-policy-society arenas such as the Sustainable Development Goals.

5. Methods

5.1. The Review of Methods and Requirements

We identified methods and their requirements based on an iterative process between the literature review and consultation with 20 researchers with different disciplinary backgrounds in natural, physical, and social sciences (S1 in supporting information). This iterative process, as used in previous studies (Carlson & Bond, 2006), helped to cover a range of documented concepts while remaining open to other suggestions for reducing the risk of a biased representation of the literature. We began by soliciting initial ideas from the literature. For methods, we reviewed suggested techniques from multiple areas where participatory modeling is being used, including environmental modeling (Voinov et al., 2018), robust decision-making (Herman et al., 2020) and the broader decision sciences (Uusitalo et al., 2015), sustainability assessment (Singh et al., 2012), and ecosystem service assessment (Harrison et al., 2018). Some of these identified methods (e.g., causal loop diagram and system dynamics modeling) and/or requirements overlapped. We represented them as separate methods/requirements if they were often used separately in past studies. We compared the identified techniques based on our co-authors' past experience from the applications of these techniques and also described our interpretation of various requirements. We expanded the initial findings from the literature with consultation through a workshop and an online survey with the participating researchers. The consultation process helped complement, collate, and prioritize the initial ideas. We then synthesized and grounded the consultation results in the literature to clarify overlap and divergences among researcher opinions and to identify further details of their suggestions (e.g., methods and their requirements) from the original sources. Finally, we sought consensus about the list of methods, selection criteria, and how they fit together through sharing a written document, containing the final results, among the researchers.

The final list of methods with their comparison and the list of practical requirements are available in S4 and S5 (supporting information). Note that this review was not meant to be exhaustive as the paper's focus was on methods/tools that could be applicable in a participatory modeling setting and with applications in sustainability research. This led us to exclude some of purely quantitative and mathematical methods (e.g., dynamic programming) from our review. We explained our approach for identifying these relevant participatory modeling methods in S3 (supporting information).

5.2. The Pathway Approach

The idea of pathways has been widely used for achieving long-term goals in an uncertain future. The socio–ecological systems area has proposed the concepts of adaptability and transformability to build capacity for transformational change through adjusting responses and crossing thresholds into new development trajectories under changing conditions (Folke et al., 2010). Sustainability and development studies also use the term pathways as an approach to *open up* for deliberation, learning, and negotiation in transition toward sustainability (Leach et al., 2010), defining pathways as "*alternative possible trajectories for knowledge, intervention, and change, which prioritize different goals, values and functions*" (Leach et al., 2010). This area also studies how methods construct politics and how pathways emerge through a political process where competing narratives about sustainability are negotiated. Decision science has used the concept of pathways in a different way—as sequences of actions and interventions to realize the transformational change in the face of *deep uncertainty* and complexity of coupled human-natural systems (Gold et al., 2019). The term deep uncertainty here recognizes that future projections, system boundary, model structure, and other aspects may not be known (or agreed among stakeholders) and may always remain unknown (Lempert et al., 2003). In this context, effective pathways are those that are robust and adaptive to future uncertainty. In this paper, we use this definition of pathway (Figure 7) and do not discuss pathways related to other areas of the literature (e.g., as how knowledge and social/political orders are co-constructed together).

The choice of the steps in the pathway development process in our article is based on the Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al., 2013, 2019) approach, which rigorously complements the concept of pathways by taking an adaptive approach (Figure 7). Although other approaches for developing pathways to sustainability exist (Gao & Bryan, 2017), we chose DAPP as it is more mature, builds upon previous analytical frameworks, and has several real-world case study applications (Zeff et al., 2016). DAPP enables researchers and practitioners to develop a set of promising adaptation pathways and signposts for transferring from one pathway to another to fulfill specified objectives. Given the pathways and signposts, informed decisions can be made in a changing environment that achieve the intended objectives despite uncertainties. Given that DAPP was originally developed for climate adaptation, we have to reinterpret the DAPP steps to incorporate the wider sphere of sustainability (Lawrence et al., 2019). Detailed information on what each step contains is available in S2 (supporting information).

5.3. Principles for Co-production of Knowledge

The framework was designed based on the following four principles for high-quality knowledge co-production for sustainability (Norström et al., 2020):

- *Context-based*: situate the methods in a particular context, place, case, and issue
- *Goal-oriented*: clearly articulate the purpose and the challenge at hand
- *Pluralistic*: explicitly recognize multiple ways of knowing and doing, and
- *Interactive*: allow for frequent interactions among actors and ongoing learning

First and second, the framework is context-based and goal-oriented as the framework identifies suitable methods in relation to the practical requirements of the case, whether they are related to specific characteristics of the context (e.g., data availability, uncertainty, and type of stakeholder involved) or the articulation of the purpose and the problem at hand (e.g., sustainable agriculture or wellbeing). Third, the framework is pluralistic in recommending suitable methods and their potential integration. The framework does not identify the best or most unique way for co-creating knowledge. Rather, it indicates the relative suitability of methods, with several methods often having similar suitability. The relative suitability of various methods across pathway development steps, negotiated between researchers from different backgrounds, can lead to alternative ways to address the same problem in a more-or-less equally effective manner, as we demonstrated in the case studies (Figure 6). Fourth, the framework enables interaction and co-learning among actors. The framework is participatory in nature by suggesting the general suitability of methods (Figure 4) and case study requirements (Figure 6) assimilating the viewpoints of the researchers and local experts. The framework promotes co-learning by making the implicit knowledge and assumptions of the research team about method capabilities and context requirements explicit, and by creating opportunities to challenge each other's assumptions through discussion and negotiation.

5.4. Assessing the General Suitability of Methods Against Requirements

The general method suitability of methods against requirements (Figure 4) was assessed based on negotiation between researchers with expertize in working with different methods, using semi-quantitative values. Method suitability was scored according to its ability to address specific requirements. To obtain researchers' assessments of method suitability, an initial list of methods and requirements was developed based on a literature review (see Section 5.1). Methods and requirements were discussed and clarified during a full-day MethodSelectionWorkshop(https://bit.ly/2V6koUp) to mitigate possible diverse perceptions among researchers about what each method can involve and what each requirement can mean. The list of methods and their requirements was distributed among the participating researchers, based on their expertize. The researchers initially evaluated the capabilities of methods qualitatively by comparing them (S4, supporting information). They then assigned a score (1: limited, 2: moderate, 3: high) to quantify method capability against each requirement. Two researchers took the coordinating role and cross-checked (and revised inconsistencies in some cases) the scores to make sure they matched the qualitative comparison of methods. The outcome of this process was a two-dimensional matrix (Equation 1), which was visualized as a heatmap in Figure 4. See S6 (supporting information) for the collected data and visualization code.

$$E\left(M\ methods \times C\ requirements\right) = \begin{bmatrix} e_{11} & \cdots & e_{1C} \\ \vdots & \ddots & \vdots \\ e_{M1} & \cdots & e_{MC} \end{bmatrix}, e_{mc} \in \mathbb{Z}^{M \times C} \tag{1}$$

e_{mc} = The suitability of method $m$to address requirement c (1, 2, and 3: higher is a more suitable method).

5.5. Assessing Method Suitability in the Case Studies

To specify suitable methods in the case studies, we initially identified the subset of requirements related to each case study selected from the full list of practical requirements (Figure 3), discussed their relative importance with local experts, and assigned a score (Equations 2 and 3) to represent the importance of each requirement, as explained below.

We scored the importance of requirements within each context, based on the synthesis of the knowledge obtained from expert elicitation in each case study and the review of published and gray literature. In the Forrest/Otways region, due to the limited literature availability, we relied more on expert elicitation from the community members to understand the contextual characteristics of the region. We ran four engagement activities (Szetey et al., 2020a), including a Listening Post and an Open House to interact with general public, a Kitchen Table Discussion and Visioning and Ideas workshop to engage with the community representatives, and several semi-structured interviews with local authorities. In the Goulburn Murray region, a rich set of documented information was available describing the context as well as a panel of local experts, consisting of technical practitioners and decision-makers from the water and agriculture sectors, who advised and verified our interpretation. We used the literature review for understanding the context (96 local reports, 34 peer-reviewed articles, and 30 transcripts of interviews with local experts) and cross checked the findings with the insights obtained from the local expert panel. The mix of engagement processes and literature review provided a comprehensive and detailed understanding of the main contextual characteristics of each region to help in scoring suitability. Detailed information about the engagement activities and the literature reviewed in each case is available as supporting data in S6 (supporting information).

We also scored the importance of the requirements at each step in the pathway development process, based on the description of each step. We initially specified the step descriptions through the review of the literature of pathway approaches (S2, supporting information). We then discussed the importance of each requirement at each step. For example, the description of the action evaluation step highlighted the ability to consider the trade-offs, synergies, and side-effects as an important quality. Given that the trade-offs and synergies were driven by complex interacting systems, we decided that "dealing with high problem complexity" was a requirement with a high importance score in action evaluation.

Method suitability was assessed in the case studies based on calculating the gap between method capabilities (Figure 4) and the case-specific subset of requirements (Figure 5), as formulated in Equation 4. The smaller the gap, the more suitable the method for the case study. We implemented the calculation of Equation 4 using the Pandas library in Python and represented the results using the heatmap function of the Seaborn library. The code is available in S6 (supporting informations).

$$W(Crequirements \times Psteps = \begin{bmatrix} w_{11} & \cdots & w_{1P} \\ \vdots & \ddots & \vdots \\ w_{C1} & \cdots & w_{CP} \end{bmatrix}, w_{cp} \in \mathbb{R}^{C \times P} \tag{2}$$

w_{cp} = the importance of requirement c in step p (0.25, 0.5, and 1.0: higher is more important); the numerical scale is selected between 0 and 1 for the normalization of final values in Equation 4.

$$R\left(G \text{ contexts} \times C \text{ requirements}\right) = \begin{bmatrix} r_{11} & \cdots & r_{1C} \\ \vdots & \ddots & \vdots \\ r_{G1} & \cdots & r_{\text{GC}} \end{bmatrix}, r_{\text{gc}} \in \mathbb{Z}^{G \times C} \tag{3}$$

r_{gc} = the importance of requirement c in context g (1, 2, and 3: higher equal to a higher importance of the requirement).

$$\begin{gathered} \text{S}\left(\text{M methods} \times P \text{ steps} \times \text{G contexts}\right) = \\ \left[\begin{bmatrix} s_{111} & \cdots & s_{1P1} \\ \vdots & \ddots & \vdots \\ s_{\text{M}11} & \cdots & s_{MP1} \end{bmatrix} \cdots \begin{bmatrix} s_{11G} & \cdots & s_{1PG} \\ \vdots & \ddots & \vdots \\ s_{M1G} & \cdots & s_{\text{MPG}} \end{bmatrix}\right], s_{\text{mpg}} \in \mathbb{R}^{\text{M} \times \text{P} \times \text{G}} \\ s_{\text{mpg}} = \frac{1}{C}\sum_{c=1}^{C} 1 - \left(\frac{1}{\text{Max}\left(r_{\text{gc}} - e_{\text{mc}}\right)}\left|r_{\text{gc}} - e_{\text{mc}}\right|\right) \times w_{cp} = \text{the suitability of method } m \end{gathered} \tag{4}$$

at step p in context g (0–1: higher is more suitable)

Data Availability Statement

Lead Contact: Further information and requests for resources and reagents should be directed to and will be fulfilled by Enayat A. Moallemi (email: e.moallemi@deakin.edu.au; Twitter: @EnayatMoallemi). The datasets/code generated during this study are available from: https://doi.org/10.5281/zenodo.4398284.

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