Main Manuscript for

Evaluating participatory modelling methods for co-creating pathways to sustainability

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Author Contributions

E.A.M. led the design, development, and writing of the article. B.A.B, F.J.D.H., M.H., S.K., S.M., A.S., M.S.S., and A.V. equally commented on and edited the article's structure and contents. R.B., P.L., K.M., E.N., W.N., E.G.R., A.M.R., M.A.S., and K.S., equally commented on the manuscript. The author names, within each of these two groups, are order alphabetically. B.A.B. designed and directed the project of which this study is a part. All authors equally contributed to the literature review of methods.

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 modelling for genuine engagement with multiple collaborators in the modelling process. Despite the diversity of participatory modelling methods to promote engagement and co-creation, it remains uncertain what the ideal 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 disciplinary backgrounds can work together and evaluate the suitability of participatory modelling 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 modelling 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.

Keywords

Sustainability; participatory; method; model; pathway; SDG.

1. Introduction

Ambitious and pressing sustainability aspirations such as the UN Sustainable Development Goals (SDGs) (*1*) require rapid and sustained transformational change over time — termed *pathways* — across local, national, and regional scales (*2, 3*). 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 (*4*). Practical research projects and science funding agencies suggest that researchers and stakeholders (i.e., local experts, decision-makers, civil society) should work together to *co-create* pathways for making progress in this complex space (*5*). Co-creation, also closely related to co-design (*6*), co-production (*7*), transdisciplinary collaboration (*8*), and post-normal science (*9*), aims to integrate science and policy and bridge divides between disciplines. Co-creation aims to generate viable pathways for addressing the complex emerging sustainability challenges and effectively influencing policymakers' decisions (*4, 7*). It also nurtures creative thinking by navigating different views amongst stakeholders and suggesting unique solutions that are contextualised for the problems at hand. Co-creation has been increasingly attained through the integration of modelling with genuine stakeholder engagement that is often framed as participatory modelling (*10*).

There is a diversity of methods available for participatory modelling (*11*). Despite increasing efforts to promote participation through these methods, it remains uncertain what the ideal amount and modes of participation are under different conditions, and how to select the suitable methods for a given situation (*12*). Pathway development also comprises multiple steps (e.g., generating scenarios, evaluating strategies) that requires various methods that can work under a different set of requirements (e.g., data availability, problem complexity, stakeholder interest). Myriad analytical methods with different requirements across the various steps of pathway analysis create a methodological dilemma in transdisciplinary research projects (*13*). A related survey that we conducted at beginning of this study showed that researchers have different views on how and when stakeholders should be engaged in pathway development (S1 in Supplementary Materials). A major source of this disagreement is rooted in biases towards past experience and disciplinary conventions (*14*). These biases in practice can often lead to a premature selection of methods that may overlook other potential alternatives for stakeholder engagement (*15*). 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 over-consultation (*16*).

Here we propose a unifying framework to evaluate and inform method selection and judiciously engage stakeholders in modelling 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 modelling methods and analyse their integration in practice. We start by identifying available method capabilities from the review of a wide range of qualitative and quantitative methods with different levels of stakeholder participation. We then identify potential requirements across various contexts for co-creating pathways, 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 analyse the suitability of methods for meeting these requirements in different sustainability contexts and for iterative steps of pathway analysis.

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 (Methods). At the highest level, the framework evaluates suitability based on how the method can address the practical requirements of a given participatory modelling situation (Figure 1). We defined practical requirements in relation to the features of the *context* (e.g., sustainable agriculture in a regional area) and across the *steps* in developing pathways (e.g., discovering future scenarios (*17*), assessing system vulnerabilities (*18*); see Figure 7 in Methods and Table S1 in Supplementary Materials for the steps' overview). Context is important since case studies are not homogenous and have various characteristics, requiring different methods. Imagine a context such as a housing development in a small town where there can be a high-level of confidence in stakeholders' predictions of the future. Here, coping with high uncertainty is not an important requirement in selecting methods for pathway development towards affordable housing. Conversely, a context such as biodiversity loss in a local area where stakeholders' knowledge of the future is limited or contested needs methods that can systematically investigate future uncertainties. Considering steps in selecting methods is important too. The co-creation of pathways typically involves several steps, 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. For example, action evaluation is a step that requires the assessment of numerous non-linear 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 methods for envisioning desired futures. Envisioning is a collaborative step aiming to reach a common understanding about what the success means; therefore it prioritises 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 modelling 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.

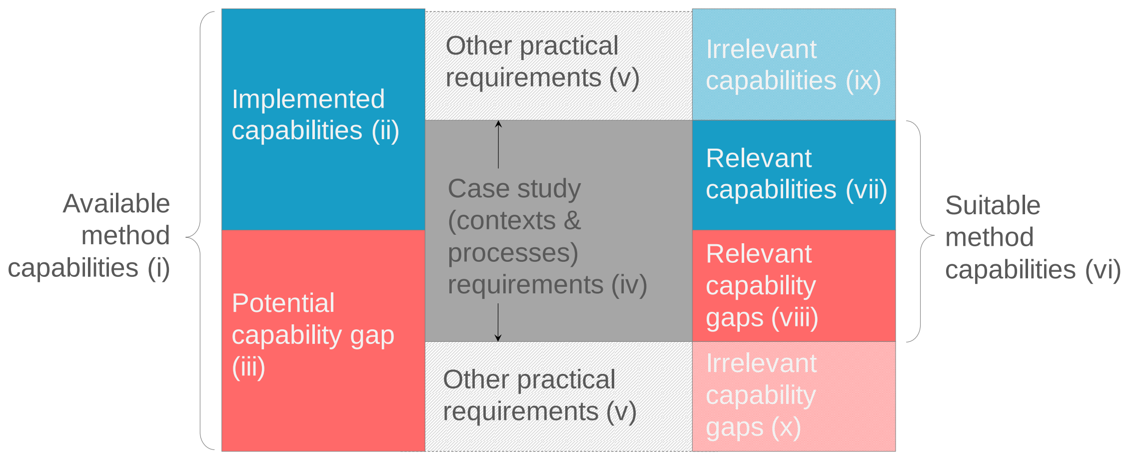

Figure 1. The framework for assessing the suitability of participatory modelling methods for co-creating pathways with stakeholders. Available method capabilities (i) are the contributions of various qualitative and quantitative participatory modelling techniques to the pathway development process. Some of this maximum range are implemented capabilities (ii) that are included in the design of participatory modelling, and some are likely not, leading to a potential capability gap (iii). The co-creation of pathways needs to address certain requirements of sustainability practice that may be common to multiple case studies. From these practical requirements, only those specific case study requirements (iv) related to the sustainability contexts and pathway development steps under study are important to address. Other practical requirements (v) unrelated to the case study are not important to address. The suitable method capabilities (vi) then become the subset of available capabilities that can address these specific case study requirements. Some of these capabilities are included in the participatory modelling design of researchers/practitioners, which we call relevant capabilities (vii). However, some others are not likely to be included, which we call relevant capability gaps (viii). These gaps need to be filled via new methods. In this framework, we do not consider irrelevant capabilities (ix) and irrelevant capability gaps (x). The former refers to method capabilities that do not address any particular case study requirements, and the latter refers to the capabilities that are not included in the researcher toolbox, but also do not address any case study requirements. The conceptual representation of the framework is inspired by Chaplin-Kramer *et al.* (*19*).

To explain how the framework helps select effective methods based on the context and steps, we need to: (a) identify method options for participatory modelling that offer different capabilities; (b) specify potential practical requirements that can impact method selection; and (c) assess method options against the practical requirements to identify those method(s) that are likely to perform better. Below we discuss these three aspects of the framework.

2.1. Identifying method capabilities in participatory modelling

Drawing on a multidisciplinary literature review (Methods), we identified a total of 43 methods which offer different yet sometimes overlapping capabilities for developing sustainability pathways. To understand these capabilities, we compared: (1) the type of problems that they can address, (2) the way they can be implemented, (3) the level of formalisation (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 (Supplementary Materials). Here we only present an overview of these methods in two dimensions (Figure 2): the level of participation and the level of formalisation.

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. 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 centred around stakeholder engagement to create a shared understanding about solutions to a common problem (*20*).

Regrading the second dimension, depending on the level of formalisation, methods can be qualitative or quantitative. Qualitative methods rely mostly on conceptualisation 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, formalised 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 analysed using standard calculations (e.g. weighted average). As the degree of quantification and formalisation of assumptions in method implementation increases, the ability to reproduce system behaviour and to validate results improve. On the other hand, relying on quantitative information may lead to diminished cultural and cognitive richness of the information compared to qualitative assessment.

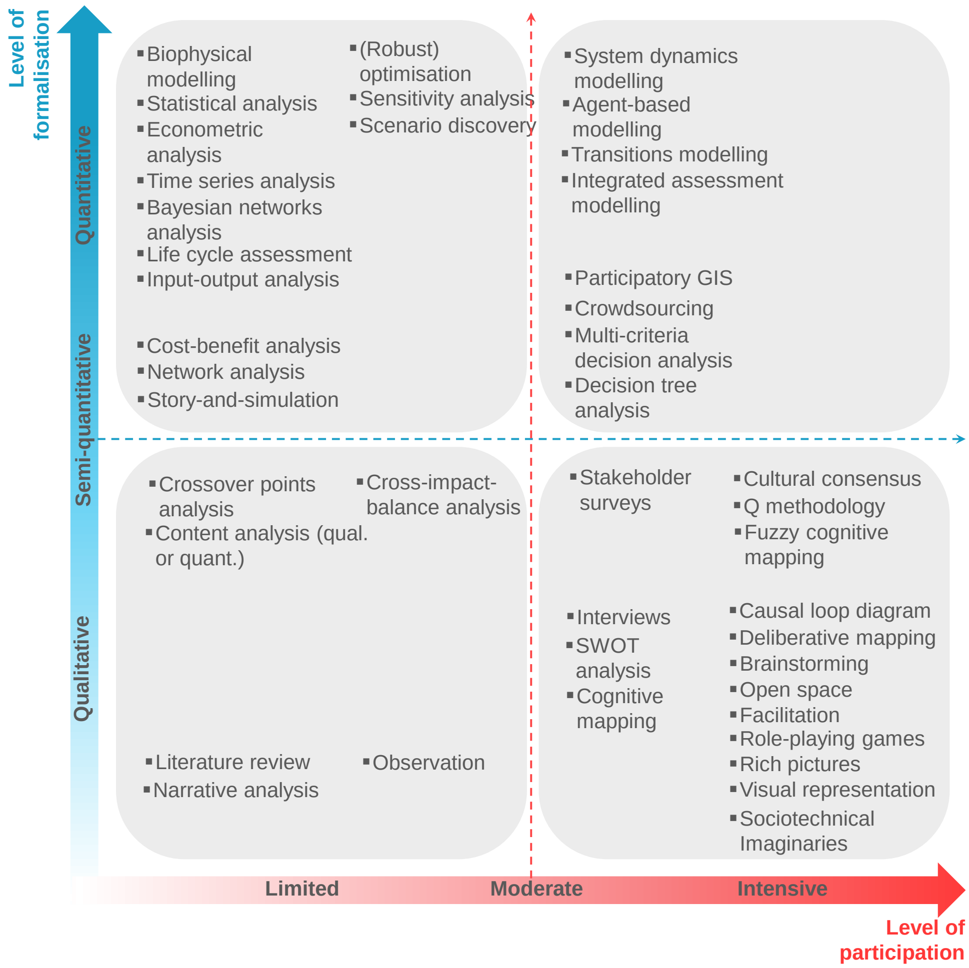

Figure 2. Identified participatory modelling methods for co-creating pathways towards sustainability goals with stakeholders. The methods vary in two dimensions: level of participation (x-axis) and level of formalisation (y-axis). A method can be more qualitative or quantitative (or equally more or less 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.

These two dimensions create four general quadrants of participatory modelling methods with different capabilities that can be used for co-creating sustainability pathways. As shown in Figure 2, the first quadrant (top-left) includes techniques for developing computational models and analysing modelling results. Some of these techniques (e.g., scenario discovery (*21*)) are supported by participatory processes while others (e.g., econometric analysis, network analysis) use available knowledge and are rarely considered as participatory. The second quadrant (top-right) 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 (*22*)) or for creating supportive or counterfactual insights to inform human judgement of complex interactions (e.g., system dynamics modelling (*23*)). The third quadrant (bottom-right) 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 imaginaries (*24*), causal loop diagrams (*25*)). The fourth quadrant (bottom-left) includes techniques suitable for collecting and analysing 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 between various factors (e.g., cross-impact-balance analysis (*26*)).

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 (Methods), we identified 27 different requirements. As shown in Figure 3, the list of practical requirements was summarised in three primary categories of outcome-oriented, research-oriented, and stakeholder-oriented, each with multiple sub-categories. The full description of these requirements is available in S5 (Supplementary Materials).

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 picture of what a successful future looks like (*27*). However, when researchers are exploring scenarios, they may better off with computational methods (e.g., scenario discovery (*17*)) 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, another 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.

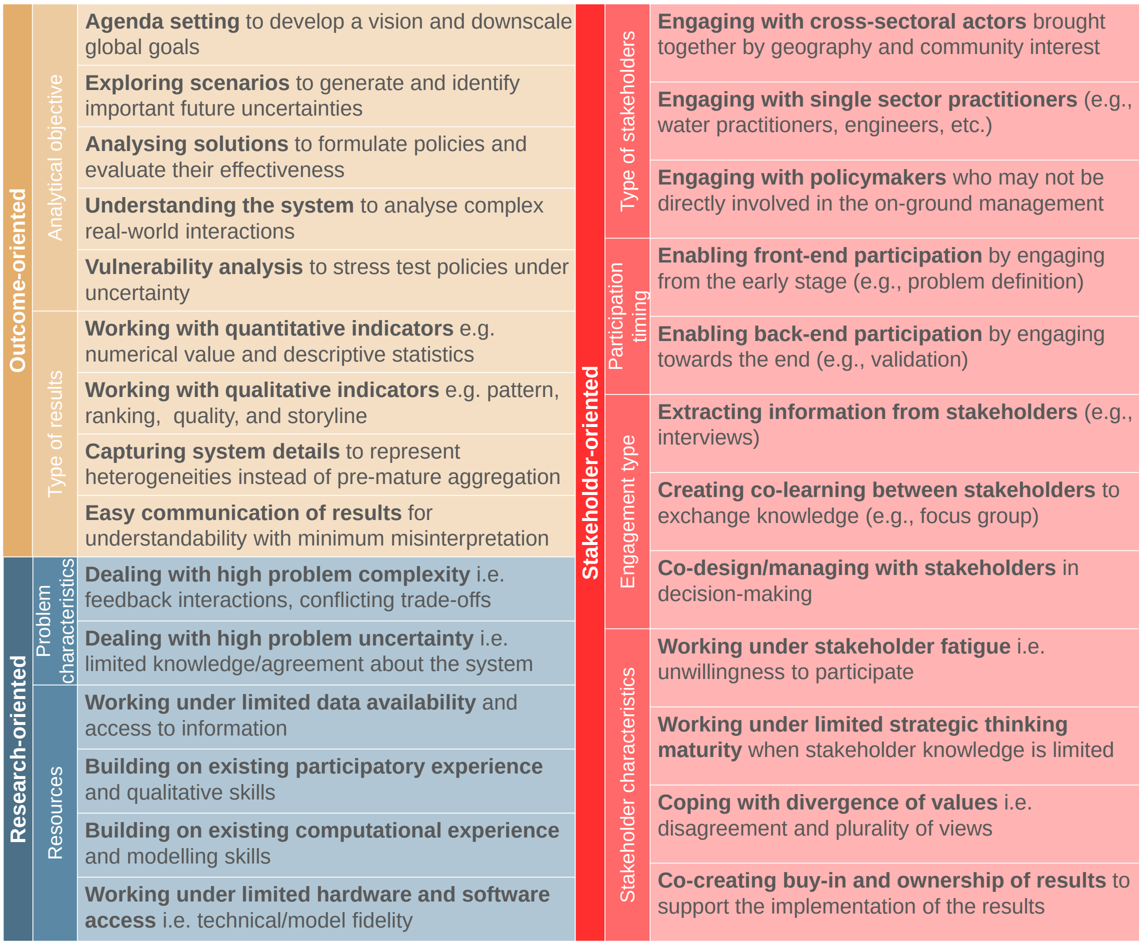

Figure 3. Practical requirements that can influence the choice of methods in co-creating sustainability pathways with stakeholders. The requirements are grouped into three categories: outcome-oriented, research-oriented, and stakeholder-oriented. In each category, the first column is the name of the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

Research-oriented requirements are related to the scientific rigour of methods to cope with the problem and the availability of resources such as data and expertise for method implementation. For example, a case study with a limited (i.e., deterministic or well-characterised) uncertainty can make good use of a method such as time series analysis (*28*) for future projection, whereas another case study with high (deep (*29*)) uncertainty would require methods that are better capable of exploring unknown futures, such as robustness techniques (*30*).

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 stakeholders are 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.

2.3. Assessing method general suitability

To assess general suitability, we analysed the extent to which method 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 optimisation (*18*) 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 (Methods and S1 in Supplementary Materials) shared their expertise and negotiated the extent to which methods can address the requirements. The results were represented in a heatmap (Figure 4). This outcome is a negotiated assessment of method suitability among the participating researchers. This general assessment of method suitability can 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 for a case study with particular requirements), and; (b) highlighting the opportunities for integration between different methods in practice (i.e., what method capabilities would be complementary for a given case study). We discuss (a) and (b) in two examples in the next section.

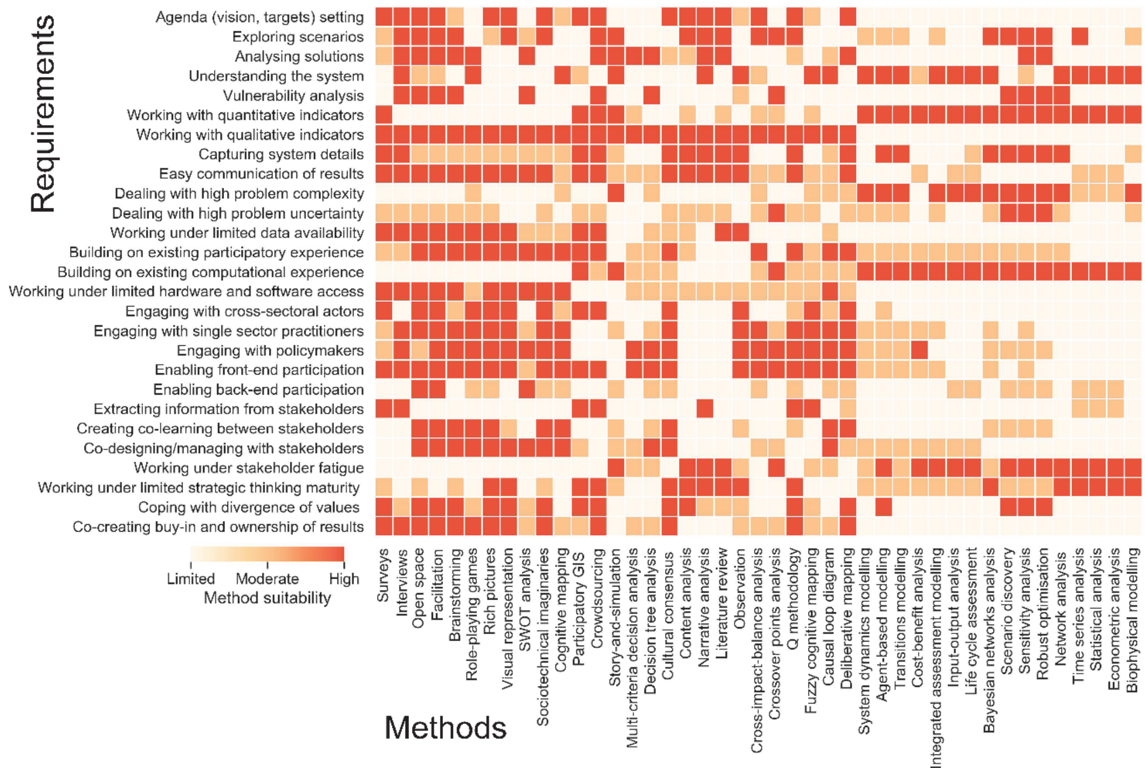

Figure 4. The general suitability of methods. The suitability is estimated based on scores assigned by researchers from different natural and social science backgrounds (Methods). The intensity of colours shows the degree of suitability: limited, moderate, and high. The higher the colour intensity, the more suitable the method in a case study, with that requirement.

3. How to use the framework in practice

The framework for the assessment of method suitability can be customised to the specific requirements of case studies, 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 (Methods): (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 *a priori* which subset of method capabilities (from the general assessment in Figure 4) meet case study requirements; (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, i.e., the Goulburn Murray and the Forrest/Otways regions, to demonstrate how these two methodological steps are implemented. Our aim in both examples was to use the framework for *a priori* evaluation to identify the best of participatory modelling methods for designing robust methodologies for pathway development in each region.

3.1. 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 expertise 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 (Methods). Figure 5 shows the importance score of the requirements in the two contexts and across the steps in the pathway development process.

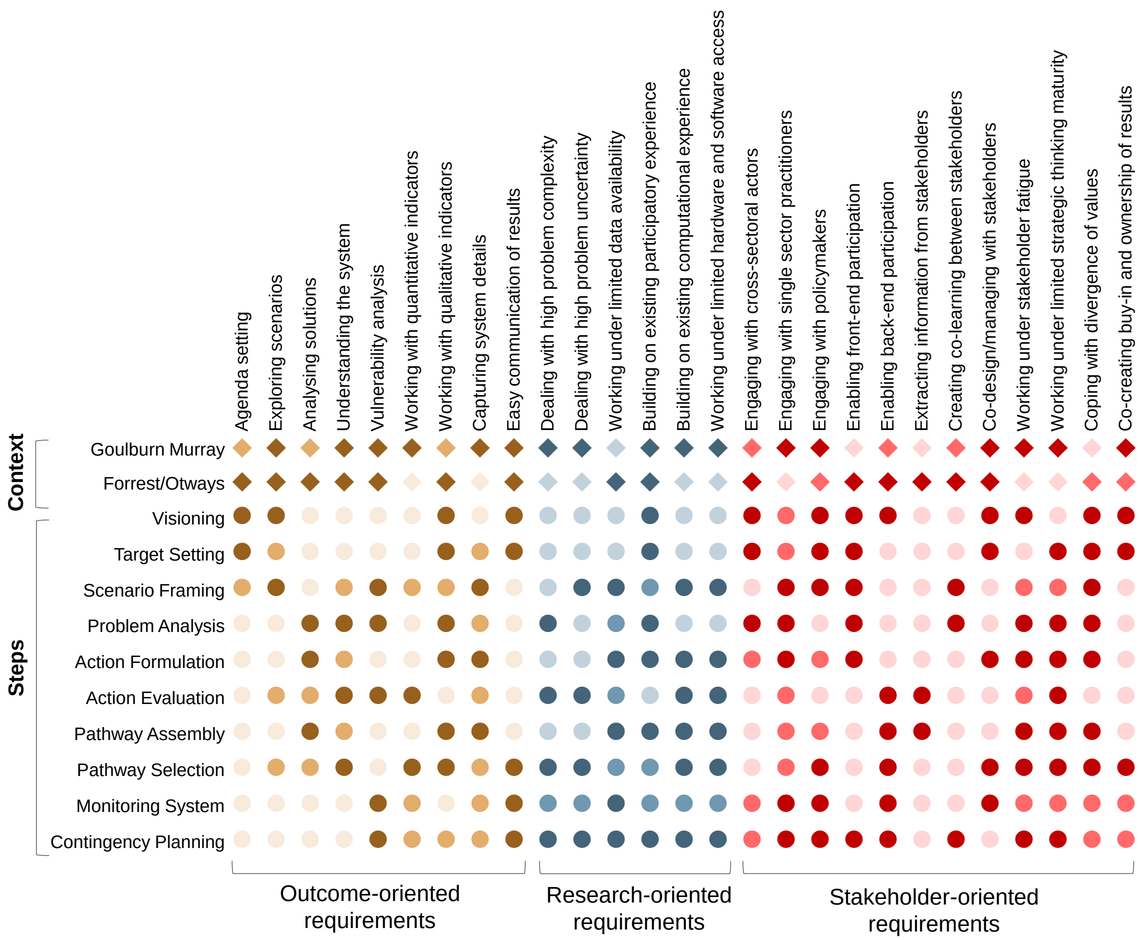

Figure 5. The specification of the practical requirements in the case studies. The intensity of colours shows the importance: low, medium, and high which varies depending on the context. For example, in Goulburn Murray, there have been several visioning exercises in the past whereas Forrest/Otways is 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 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 (Methods).

Specification of case-specific requirements showed that requirements can differ in importance between case studies. The cases had different contexts characterised by various sustainability priorities, engagement fatigue, and documented information availability. The Goulburn Murray region, known as the 'food bowl of Australia', has been long subjected to strategic planning and intensive engagement activities aimed at promoting sustainable agriculture among other sustainability goals (*31*). 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. The context of this case is characterised 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 Methods.

In addition, the specification of case-specific requirements showed that the importance of practical requirements varied amongst the steps of the pathway development process. We evaluated method suitability through multiple steps originally framed by Haasnoot et al. (*32*) (Figure 7). They start with visioning and target setting where a long-term desirable future with measurable goals and targets is defined. Then the 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 analysed (i.e., problem analysis, action formulation, action evaluation). The sequence of actions together creates pathways towards long-term goals (i.e., pathway assembly, 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 Methods and in S2 (Supplementary Materials). Each of these steps, depending on their aim and expected outcomes in pathway development, required a set of different 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 analyse 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 Methods.

3.2. Evaluating method suitability in case studies

We explored and evaluated the suitability of methods in 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 (Methods). The results are represented in a heatmap in Figure 6. As a general overview, the case-specific assessment showed that suitable participatory modelling methods with different levels of engagement with stakeholders can vary 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 (*33*). For example, in Goulburn Murray, a set of contextual characteristics, such as priority for quantitative agricultural production indicators, availability of models and datasets, and stakeholder reluctance for engagement, made modelling methods rather than participatory, more suitable for pathway development. More specifically, modelling approaches such as integrated assessment modelling (*34*) and transitions modelling (*35*), in conjunction with computational techniques such as sensitivity analysis and scenario discovery (*21*) were among the top five most suitable methods. 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 measure the progress towards targets on food and agriculture production.

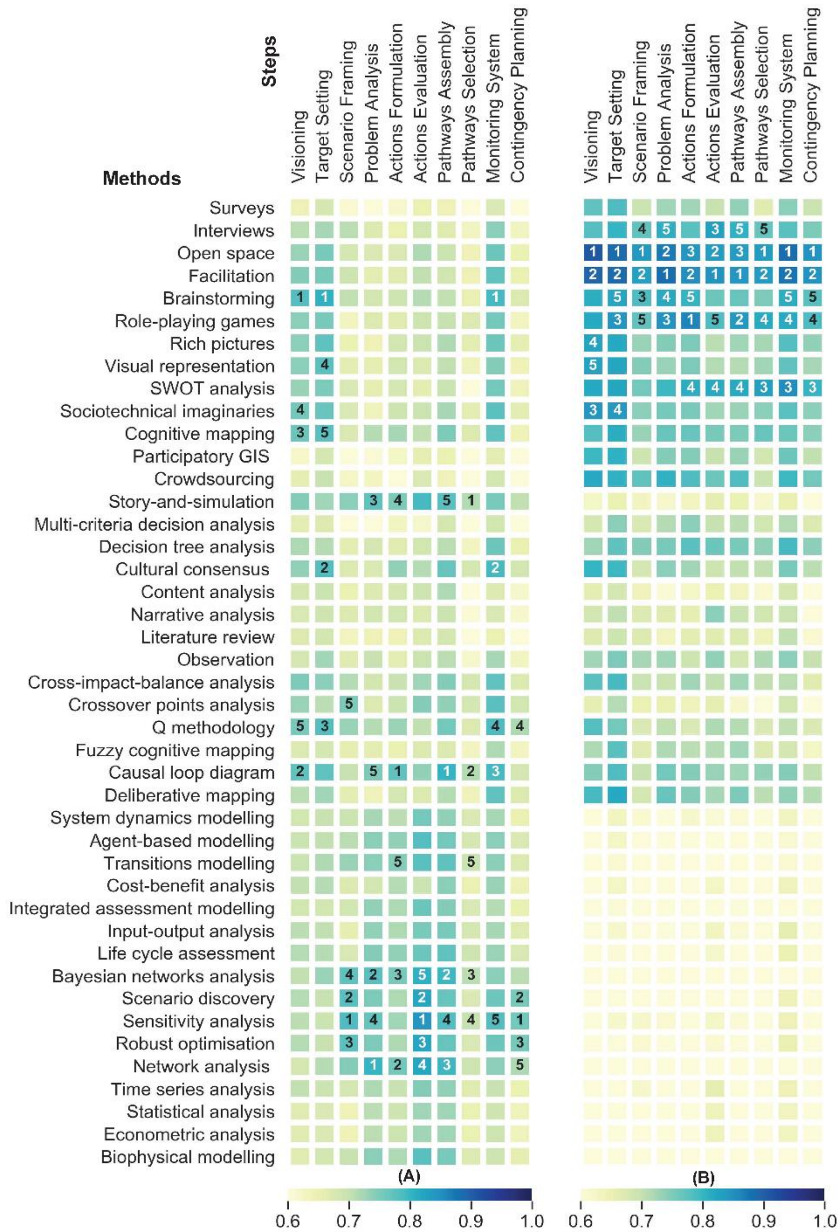

Figure 6. The suitability of methods for co-creating sustainability pathways in two case studies: (A) Goulburn Murray; (B) Forrest/Otways. The rows in the heatmaps are methods. The columns are the steps in the pathway development process. The intensity of colour represents method suitability in each case and in each step. The numbers in the heatmap cells indicate the top five suitable methods with the highest score at each step.

The outcome, however, limited the use of participatory and qualitative methods to a supporting role for model development and analysis. For example, a method such as cognitive mapping was among the top five methods because it could be used to elicit stakeholder inputs to inform the model development process and to create consensus about the boundary of problems to analyse.

Game-based learning and role-playing games (*36*) were also among participatory and qualitative methods that were regarded as suitable because of their capability in capturing the diversity of stakeholder responses to the changing dynamics of the system, which could help in testing model outputs.

The suitability of methods was, however, different in the case of Forrest/Otways. Highly participatory and qualitative methods were identified among the top five techniques. It 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 (*37*) and sociotechnical imaginaries (*24*) were among the top five most suitable methods as they could help in exploring the future through visioning, downscaling global goals to local priorities, and constructing scenarios. The high diversity of views among stakeholders also made methods such as role-playing games (*36*) and SWOT analysis (*38*) 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., facilitation and rich pictures (*39*)) 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, a method such as scenario discovery (*21*) 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 methods such as integrated assessment modelling (*34*) combined with robust optimisation (*18*) were identified as suitable in action evaluation and pathway assembly. They were thought to be helpful in simulating and analysing the efficacy of contested strategies proposed by various stakeholder groups over space and time. They were also useful as they could inform 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 such as visioning and target setting.

Method suitability in the two case studies was undertaken prior to the co-creation of pathways. *A priori* evaluation should be regarded as a starting point, helping to acknowledge different perspectives in coping with complex transdisciplinary problems. It was intended to facilitate an effective flow of information and to enable transparent communication among researchers from the extended scientific communities involved. Therefore, the results should not be interpreted as ‘‘the right answers’’. Rather, they should be regarded as a negotiated outcome among collaborating researchers and a changed practice based on evidence from case studies and expert elicitation instead of disciplinary biases.

3.3. Re-evaluating method suitability through reflection

A priori evaluation was based on the best available knowledge of the requirements of each case study and what each method could offer at the start of the pathway development project. Contexts and requirements however, can change due to irreducible uncertainties and the emergence of new information over time (*40*) and this can challenge the method implementation. There may be also knowledge gaps about whether a method suits a context and can be implemented successfully. For example, misperceptions about access to data and model fidelity when deciding about model-based approaches could later require a change of method. Context can also change over time which can alter the relative suitability of methods. For example, travel restrictions as a result of the global COVID-19 pandemic has changed how researchers can interact with stakeholders. These changes necessitate method re-evaluation which will help assess whether the methods selected *a priori* will continue to deliver the best outcomes (*33*), of if other methods should be considered as new conditions emerge (*41*).

While the success in formal disciplinary approaches is often defined based on conventional performance metrics such as efficiency and improvement in outcomes, the final measure of a collaborative exercise in complex socio-ecological problems with multiple stakeholders should be different (*42*). Realising impact in transdisciplinary research, including the case studies presented here, should be measured based on the broader achievements and cross-domain learnings between participants in the long-term. A better outcome should be defined in relation to addressing the expectations of participating researchers and engaging with research users to design and execute pathways aligned with their needs. Here the reflexive use of our suggested framework becomes important to provide quality assurance in choosing suitable methods and to promote accountability between researchers in implementation. There is an extensive literature about reflection on theory and methods (*33*) as well as how reflection should be used to inform participatory modelling (*43*). Among them, Roux *et al.* (*33*) and Zare *et al.* (*43*) 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.

4. Implications for the global 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 the desired outcomes. There is no *unique* or *best* combination of participatory and modelling methods for sustainability in practice, and often different methods can address the same problem effectively (*44*). 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. A systematic framework which has both a method toolbox and the assessment of their available capabilities can significantly help researchers in deciding which method to use and when to use it. Second, we expect this research to inform the effective integration of various methods in a way that can complement the limitations of one with the strengths of another. 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*" (*43*). The proposed framework for the assessment of method suitability can make method integration more systematic and transparent and offers researchers a wider view of the range of techniques available for co-creating pathways. The framework also offers guidelines for how to select suitable methods to effectively integrate participatory processes and models.

The proposed framework can contribute to the transdisciplinary understanding of sustainability assessment 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.

Methods

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 Supplementary Materials). This iterative process, as used in previous studies (*45*), 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 modelling is being used, including environmental modelling (*10*), robust decision-making (*30*) and the broader decision sciences (*46*), sustainability assessment (*47*), and ecosystem service assessment (*13*). Some of these identified methods (e.g., causal loop diagram and system dynamics modelling) and/or requirements overlapped. We represented them as separate methods/requirements if they were used separately at least in some past studies. We compared the identified techniques by reviewing three articles (on average) for each method (S4 in Supplementary Materials) and described the requirements as well (S5 in Supplementary Materials). 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 prioritise the initial ideas. We then synthesised 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. These steps are further explained in S3 (Supplementary Materials).

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 (*48*). Sustainability and development studies also use the term pathways as an approach to *open up* for deliberation, learning, and negotiation in transition towards sustainability (*49*), defining pathways as "*alternative possible trajectories for knowledge, intervention, and change, which prioritise different goals, values and functions*" (*49*). 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 and as sequences of actions and interventions to realise the transformational change in the face of *deep uncertainty* and complexity of coupled human-natural systems (*18*). The term deep uncertainty here recognises that future projections, system boundary, model structure, and other aspects may not be known (or agreed among stakeholders) and may always remain unknown (*29*). In this context, effective pathways are those that are robust and adaptive to future uncertainty. In this paper, we use this definition of pathway from decision science (Figure 7) and do not discuss pathways as, e.g., how knowledge and social/political orders are co-constructed together, related to the other areas of the literature.

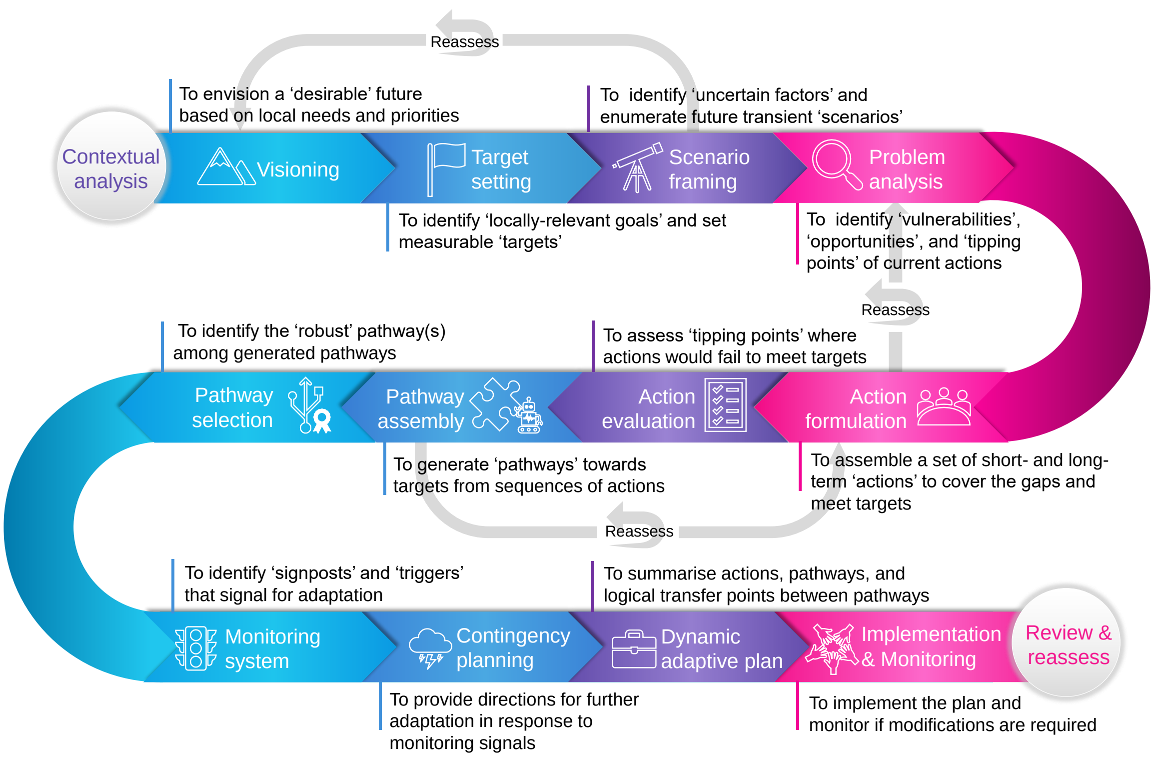

Figure 7. An overview of the steps in developing pathways towards sustainability goals. The process is iterated over time as the knowledge about the system and its context increases. Adapted from Haasnoot et al (*32*).

The choice of the steps in the pathway development process in our article is based on the Dynamic Adaptive Policy Pathways (DAPP) (*32*) approach which rigorously complements the concept of pathways by taking an adaptive approach (Figure 7). Although other approaches for developing pathways to sustainability exist (*2*), we chose DAPP as it is more mature, builds upon previous analytical frameworks, and has several real-world case study applications (*50*). DAPP enables researchers and practitioners to develop a set of promising adaptation pathways and signposts for transferring from one pathway to another to fulfil 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. Detailed information on what each step contains is available in S2 (Supplementary Materials).

Principles for co-production of knowledge

The framework was designed based on the following four principles for high-quality knowledge co-production for sustainability (*7*):

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

First, the framework is context-based and goal-oriented as the framework identifies suitable methods in relation to the practical requirements of case studies; whether they are related to specific characteristics of the context (e.g., data availability, uncertainty, type of stakeholder involved) or the articulation of the purpose and the problem at hand (e.g., sustainable agriculture or wellbeing). Second, 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 possible alternative ways to address the same problem in a more-or-less equally effective manner, as we demonstrated in the case studies (Figure 6). Third, 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 the context requirements explicit, and by creating opportunities to challenge each other’s assumptions through discussion and negotiation.

Assessing the general suitability of methods against requirements

The general method suitability (Figure 4) of methods against requirements was assessed based on negotiation between researchers with expertise 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 previous section above).

Methods and requirements were discussed and clarified during a full-day Method Selection Workshop (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 were distributed amongst the participating researchers, based on their expertise. The researchers initially evaluated the capabilities of methods qualitatively by comparing them (S4, Supplementary Materials). 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 (Eq. 1) which was visualised as a heatmap in Figure 4. See S6 (Supplementary Materials) for the collected data and visualisation code.

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

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

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 (Eq. 2 and Eq. 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 grey 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 (*51*), 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 information 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 (Supplementary Materials).

We also scored the importance of the requirements at each step in the pathway development process, based on the description of each step. They initially specified the step descriptions through the review of the literature of pathway approaches (S2, Supplementary Materials). They 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 Eq. 4. The smaller the gap, the more suitable the method for the case study. We implemented the calculation of Eq. 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 (Supplementary Materials).

$$W\ (C \text{ requirements} \times P \text{ steps}) = \begin{bmatrix} w_{11} & \cdots & w_{1P} \\ \vdots & \ddots & \vdots \\ w_{C1} & \cdots & w_{CP} \end{bmatrix},\ w_{cp} \in \mathrm{R}^{C \times P}, \tag{2}$$

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 normalisation of final values in Eq. 4.

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

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

S (M methods$\times P$ steps$\times G$ contexts)

$$= \begin{bmatrix} \begin{bmatrix} s_{111} & \cdots & s_{1P1} \\ \vdots & \ddots & \vdots \\ s_{M11} & \cdots & s_{MP1} \end{bmatrix} & \cdots & \begin{bmatrix} s_{11G} & \cdots & s_{1PG} \\ \vdots & \ddots & \vdots \\ s_{M1G} & \cdots & s_{MPG} \end{bmatrix} \end{bmatrix}, \quad s_{mpg} \in \mathrm{R}^{\mathrm{M \times P \times G}}, \tag{4}$$

$s_{mpg} = \frac{1}{C}\sum_{c=1}^{C} 1 - \left(\frac{1}{Max\left(r_{gc} - e_{mc}\right)} \left| r_{gc} - e_{mc} \right| \right) \times w_{cp}$ = the suitability of method m at step p in context g (0 – 1: higher is more suitable)

Acknowledgments

This work is funded by The Ian Potter Foundation and Deakin University.

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