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Knowledge co-production for decision-making in human-natural systems under uncertainty

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ABSTRACT

Decision-making under uncertainty is important for managing human-natural systems in a changing world. A major source of uncertainty is linked to the multi-actor settings of decisions with poorly understood values, complex relationships, and conflicting management approaches. Despite general agreement across disciplines on co-producing knowledge for viable and inclusive outcomes in a multi-actor context, there is still limited conceptual clarity and no systematic understanding on what co-production means in decision-making under uncertainty and how it can be approached. Here, we use content analysis and clustering to systematically analyse 50 decision-making cases with multiple time and spatial scales across 26 countries and in 9 different sectors in the last decade to serve two aims. The first is to synthesise the key recurring strategies that underpin high quality decision co-production across many cases of diverse features. The second is to identify important deficits and opportunities to leverage existing strategies towards flourishing co-production in support of decision-making. We find that four general strategies emerge centred around: promoting innovation for robust and equitable decisions; broadening the span of co-production across interacting systems; fostering social learning and inclusive participation; and improving pathways to impact. Additionally, five key areas that should be addressed to improve decision co-production are identified in relation to: participation diversity; collaborative action; power relationships; governance inclusivity; and transformative change. Characterising the emergent strategies and their key areas for improvement can help guide future works towards more pluralistic and integrated science and practice.

1. Introduction

Nature, people, and policy co-evolve and are inextricably interlinked (Serrao-Neumann et al., 2021), giving increasing importance to an integrated understanding of human-natural systems in recent decades (Liu et al., 2007). A long history of studying human-natural systems has focused on their planning, management, and decision-making under uncertainty to inform complex challenges in a changing world (Marchau et al., 2019; Reed et al., 2022; Simpson et al., 2016). These can include the management of global commons (Dolan et al., 2021), climate change mitigation (Giuliani et al., 2022), adaptation (Haasnoot et al., 2021), sustainable development (Liu et al., 2023), among others.

Within human-natural systems, a major source of uncertainty stems from their multi-actor settings (Srikrishnan et al., 2022). These actors can include individual citizens, local/Indigenous communities, technical experts, NGOs and advocacy groups, industry/business partners,

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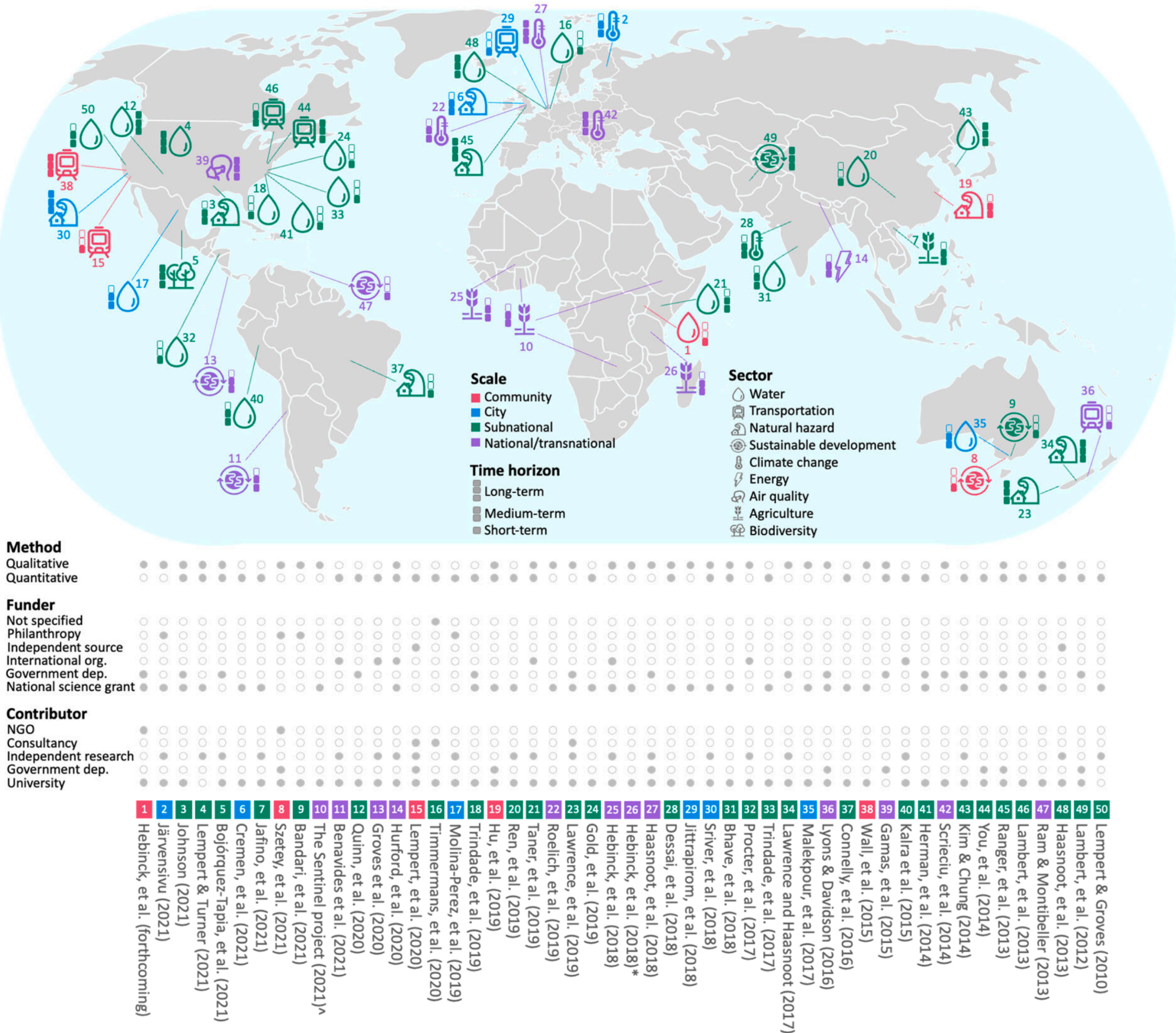

Fig. 1. The case studies analysed for their decision co-production. Cases are related to decision-making under uncertainty and are selected in the context of human-natural systems. Online access to all cases is available in the case details tab in Supplementary Data 2. * Hebinck et al. (2018) is listed twice as it focuses on multiple cases with different features.^This study includes multiple cases including (Gebrehiwot and Zurek, 2018; Kwenye et al., 2018; Neina et al., 2018), but it was listed once due to method similarities. Icons for water, transportation, natural hazards, sustainable development, climate change, energy, air quality, agriculture, and biodiversity are by IYIKON, Rolas Design, Georgiana Ionescu, Ahmad Roaayala, Tomas Knopp, Amelia Jannah, Alex Quinto, Andrejs Kirma, and Rolas Design (respectively) from Noun Project under a Creative Commons License CC BY 3.0. (See above-mentioned references for further information.)

financial sector/markets, and government/decision-makers. They have relevant stakes and knowledge and create a plurality of human interests, conflicting policy objectives, and behavioural and institutional ambiguity (Reed et al., 2009).

Making decisions under the uncertainty of multi-actor settings increasingly requires deeper integration with different world-views (e.g., people's cultural values, human preferences) and diverse knowledge and policy experience (e.g., decision-maker's conflicting objectives, power relationships) (Constantino and Weber, 2021). This integration is often through approaches that support interactive arrangements among diverse actors to define focal issues, explore research options, and deliver societal outcomes. Such processes that link the diverse values that people want to advance with the knowledge required to do so is referred to as *co-production* (Norström et al., 2020). Co-production promises to improve decision quality through deliberation and collaborative management by fostering viable, fair, and inclusive decision options and solutions (Turnhout et al., 2020).

To realise the compelling promise of co-production, a variety of recent practice-oriented, theoretical, and empirical contributions have started to provide guidance for engaging diverse actors in scientific work (Chambers et al., 2021; Norström et al., 2020; Serrao-Neumann et al., 2021; Yoon et al., 2022). Studies have used different theories and terminologies such as co-creation (Mauser et al., 2013), co-design (Moser, 2016), co-production (Wyborn et al., 2019), co-engineering (Daniell et al., 2010), governance partnership (Moss et al., 2021), action-oriented knowledge (Caniglia et al., 2021), transdisciplinary and participatory research (Michas et al., 2020), and post-normal science (Funtowicz and Ravetz, 1993). They have also employed various qualitative and quantitative approaches that combine computational and human capabilities interactively (Moallemi et al., 2021; Voinov et al., 2018). These advances have made co-production a cornerstone of managing human-natural systems. Its importance in the serving both societal and policy change is widely recognised (Reed et al., 2022; Wyborn et al., 2019). There is also wide acknowledgement that the forms and extent of co-production, and ultimately the need for it, will vary across contexts depending on the stakes in play and degree of stakeholder disagreement about outcomes (Leith et al., 2017; Moallemi et al., 2021). For instance, automated monitoring and evaluation of energy production and use will involve less co-production than siting of a nuclear waste disposal facility.

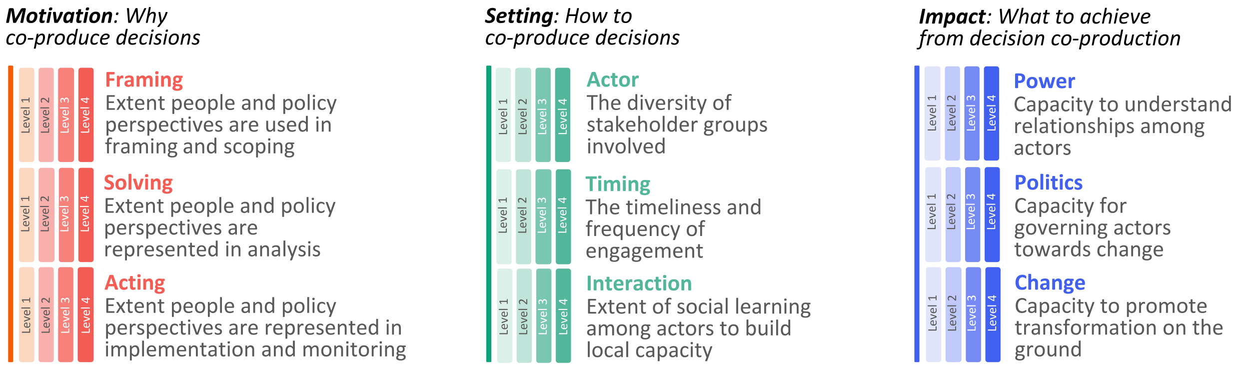

Fig. 2. A summary of features used to characterise the decision co-production cases. See Supplementary Text for definitions of each feature and their guiding levels.

Despite significant work in areas such as sustainable development (Chambers et al., 2021), climate change (Bremer and Meisch, 2017), conservation (Dawson et al., 2021), and ecosystem services (Hinson et al., 2022), there is still poor conceptual clarity about co-production approaches that are targeted to planning, decision-making, and management of human-natural systems under uncertainty (hereafter, in short, decision co-production). We argue that research on decision-making is in a stage of maturation where it has need of a comprehensive evaluation of: Where do we stand in working with actors and stakeholders? What are the gaps? How to address them?; that can be a point of reference for co-production in decision-making.

Past efforts in decision co-production have been limited by focusing on specific sectoral domains (e.g., water (Zare et al., 2021)), individual processes (e.g., problem formulation (Lempert and Turner, 2021), scenario framing (Rutting et al., 2021)), and certain interaction modes (e.g., eliciting information (Taner et al., 2019), social learning (Järvensivu et al., 2021)). These limited foci indicate a distinct lack of understanding from the diversity of decision co-production strategies and no clear articulation of its challenges and opportunities to guide the future development of the planning and decision-making field.

Here, we analyse 50 case studies that have involved societal actors (or have provided methodological opportunities for co-production with them) in decision-making under uncertainty. To reflect on a wide range of empirical experience, our cases are diverse in terms of time horizon (i.e., short-, medium-, long-term), spatial scale (i.e., sub-national, national, transnational), sectoral focus (e.g., water, energy, climate, agriculture, infrastructure, conservation), and geographical location (i.e., Asia, Africa, North, Central, and South Americas, Europe, Oceania) (Fig. 1). Examples of these cases are participatory urban water robust decision-making in Mexico (Molina-Perez et al., 2019), co-development of agriculture scenarios in Africa (Gebrehiwot and Zurek, 2018), and sustainability planning with local communities in Australia (Szetey et al., 2021b). We characterise the cases' distinct choices, differences, and trade-offs through content analysis and clustering methods (Section 2). This serves two aims. The first is to synthesise key recurring strategies through which co-production is motivated, designed, and leads to impact in decision-making under uncertainty (Section 3). Characterising these strategies is important to define what co-production means in decision-making and in what ways it can be achieved. The second aim is to build on this existing empirical evidence by learning from their strengths and limitations and highlighting opportunities for successful decision practices in the future (Section 4). This can lead to a deeper understanding of the barriers in realising the strategies of effective co-production and provide recommendations to design inclusive decision processes with fair outcomes.

2. Methods

2.1. Case selection

We selected a mix of cases (e.g., qualitative, quantitative) of decision-making under uncertainty for an in-depth analysis of co-production strategies. We used a hybrid method for case study selection using a systematic search of the literature and suggestions from co-authors who are experts in the field of decision science and/or knowledge co-production. This hybrid method helped improve the diversity of cases in terms of systems, locations, and scales by remaining open to other suggestions. The hybrid method is common practice, used to address the inherent limitations of a systematic search which is restrictive in selecting relevant studies and may miss interesting cases due to fixed search strings and the limited scope of search databases (Grant and Booth, 2009).

The details of the systematic search are explained in Supplementary Text (e.g., database, keywords, selection criteria, search results). This systematic search resulted in 246 publications (Supplementary Data 1), 36 of which were identified as relevant based on the four selection criteria of context-based (i.e., being real-world case), goal-oriented (i.e., focusing on a decision problem under uncertainty), pluralistic (i.e., acknowledging co-production), and interactive (i.e., engaging with societal actors). These criteria led to a certain sub-set of relevant co-production cases, which when later dissecting the differences among that set, will highlight distinctions in decision co-production (e.g., how they are motivated, through which settings, and for what impacts). Additionally, we included 14 other cases suggested by co-authors and relevant to the selection criteria which did not appear in the systematic search results. Together, they formed 50 case studies to be used for content analysis (Supplementary Data 2).

2.2. Content analysis

To synthesise the key strategies from the selected cases, we performed *content analysis.* First, we extracted a set of *meta*-information from the selected cases, including source title (or journal), year (of publication or case study), contributor's organisation (i.e., university, government department, independent research unit, consultancy, NGO), funding source (i.e., national science grant, government department, international organisation, independent source, philanthropy), geographical location, scale (i.e., community, city, subnational, national/transnational), time horizon (i.e., short-term, medium-term, long-term), sector (e.g., water, climate change, energy), and methods (i.e., qualitative, quantitative, both). See the case details tab in Supplementary Data 2. These were later used in characterising the cases in the analysis.

Second, we read the collected articles related to case studies in detail and coded their contents against the nine characterising features (Fig. 2) in relation to motivation for co-production (i.e., *Framing, Solving, Acting*), settings for engagement (i.e., *Actor, Timing, Interaction*), and impact materialised on the ground (i.e., *Power, Politics, Change*).

- **Motivation:** The first three characterising features pertained to the motivation and purpose of integrating inputs from societal actors (i.e., *why* co-produce). Past studies have articulated them with slight variations in terminology and level of detail (Kwakkel and Haasnoot, 2019; Moallemi et al., 2020; Simpson et al., 2016; Walker et al., 2013). In line with these previous studies, we broadly categorised the motivation for decision co-production as: *Framing* (a.k.a. decision scoping (Simpson et al., 2016), priority setting (Bandari et al., 2021), problem formulating (Lempert and Turner, 2021), stage setting (Kwakkel et al., 2010), future framing (Hebinck et al., 2018)); *Solving* (a.k.a. analysing problems (Moallemi et al., 2021), evaluating options (Gold et al., 2019), assessing scenarios (Hadjimichael et al., 2020)); and *Acting* (a.k.a. executing and implementing (Haasnoot et al., 2013), communicating (Szetey et al., 2021b), monitoring and evaluating (Haasnoot et al., 2018)).
- **Setting:** The next three characterising features described the arrangements laid out towards the co-production purposes (i.e., *how* to co-produce?). For example, one case may choose to engage with actors who have technical expertise to collect necessary information whereas another case may choose to engage with broader societal actors (e.g., local communities) to facilitate co-learning and to collaboratively design the plan. We described the diversity of transdisciplinary arrangements for decision co-production in terms of: *Actor* (Reed et al., 2009) to explain which stakeholder groups, at different levels of stake and influence, participated in co-production; *Timing* (Halbe, 2019) to indicate when (e.g., beginning, end) and with what frequency (i.e., once, twice, multiple times) they engaged with actors throughout decision-making; and *Interaction* (Lynam et al., 2007) to specify the direction of information circulation and exchange of information (i.e., one way, two-way, interactive).
- **Impact:** Decision co-production is not only about improving scientific efforts, but also about creating the potential for outcomes or impacts on the ground. This relates to understanding and engaging with how politics and power relationships among actor groups are shaped and influence decisions, how solutions are seen as legitimate, how they are implemented, and how they eventually lead to societal change (Moss et al., 2021). The last three characterising features were about thinking through change and described the ways in which the impacts from decision co-production are intended to be catalysed (*what* to achieve?). We used three conceptualisations of impact (Chambers et al., 2021; Turnhout et al., 2020) in terms of: *Power* (Avelino, 2021; Gold et al., 2022) as understanding relationships among actors (e.g., ability to create or resist change, influence over others, conflicts and cooperation); *Politics* (Turnheim et al., 2015; Turnhout et al., 2020) as the act of governance for managing towards change through actors and choosing who should do what and through which means to instigate and realise decisions; and *Change* (Schneider et al., 2019a; Schneider et al., 2019b) as the guidance of transformation on the ground. Note that these three features are about intended outcomes, capacity to think through impact, and guiding measures on the ground, as opposed to *a posteriori* evaluation of actual outcomes and impact assessment after implementation.

These nine characterising features may not be fully comprehensive in showing all decision co-production qualities, but they covered a range of important ideas in relation to decision co-production. They built on previous work on analytical objectives in decision-making related to Motivation (Herman et al., 2020; Moallemi et al., 2020), conditions of participatory modelling related to Setting (Halbe, 2019; Voinov et al., 2016), and the role of human agency and societal change related to Impact (Avelino, 2021; Chambers et al., 2021).

We mapped the quality of co-production in the cases against these nine characterising features. For each feature, we characterised the cases using four guiding levels that show the extent of co-production, with Level 1 as no discussion and limited opportunity and Level 4 as detailed discussion and substantial opportunities (Fig. 2). See the definition of each level in Supplementary Text. The outcome of content analysis was a coding database, including numbers from 1 to 4 (indicating Level 1 to 4) for each case and in each feature to be used later for clustering (Supplementary Data 2 and 3).

2.3. Clustering

Despite differences between the cases, they often share certain similarities in co-producing decisions. Therefore, it's important to identify the recurring patterns (i.e., strategies) that are emerging from these similarities and differences; those that transcend the details of individual cases and can be meaningful in broader decision co-production. Given the large number of cases, comparative features, and their coding levels (50 cases × 9 features × 4 levels), these patterns cannot be synthesised manually. We performed *clustering* to group the cases based on their similarity in relation to the nine characterising features and synthesise the general co-production strategies. To cluster the coded cases from content analysis, we used a *k-means* clustering algorithm that is commonly used in quantitative analysis on the basis of its performance compared with other algorithms (Jafino and Kwakkel, 2021). Its performance is evaluated by the explained variance metric (EV_k) in Equation (1), where K is the number of clusters, SSE_k is the sum of squared error of cases in cluster k, and SSE_{all} is the sum of squared error across all cases.

$$EV_k = 1 - \sum_{k=1}^{k} SSE_k / SSE_{all} \quad (1)$$

The higher the number of clusters, the smaller the differences between cases in each cluster. However, by increasing the number, clusters of similar features may emerge and therefore there is a potential loss in interpretability. Decision on the optimal number of clusters was made by increasing the number of clusters from 2 to 10 and tracking explained variance for different cluster numbers (Supplementary Fig. 1). We specifically looked at the changes in explained variance (Equation (2) which indicates how much an additional cluster would improve the explained variance.

$$\Delta EV_k = EV_k - EV_{k-1} \quad (2)$$

Following the process set in a previous study (Jafino and Kwakkel, 2021), we used a subjective threshold (T) of 0.05 for the changes in explained variance to understand when convergence occurs ($\Delta EV_k < T$), and therefore to identify the optimal number of clusters. This led to four clusters as the optimal number (Supplementary Fig. 1). The k-means algorithm used this optimal number of clusters and classified the cases based on their similarities into four clusters. Code and supporting computation for clustering and decision on cluster numbers are available in Code and Data Availability.

2.4. Gap analysis

The strategies identified through clustering came with strengths and limitations, represented in their different extents of co-production (i.e., high and low levels coded against the nine features). We focused on those features that were less developed (i.e., mapped with lower levels in content analysis) to specify some of the important gaps in decision co-production. We then discussed ways to address these gaps in the future by learning from best practices among our selected cases. In discussing the ways to address the gaps, we also referred to several tools and approaches beyond our cases to capture opportunities for decision co-production from the broader literature. The gaps and the ways to address them indicated areas for future improvement.

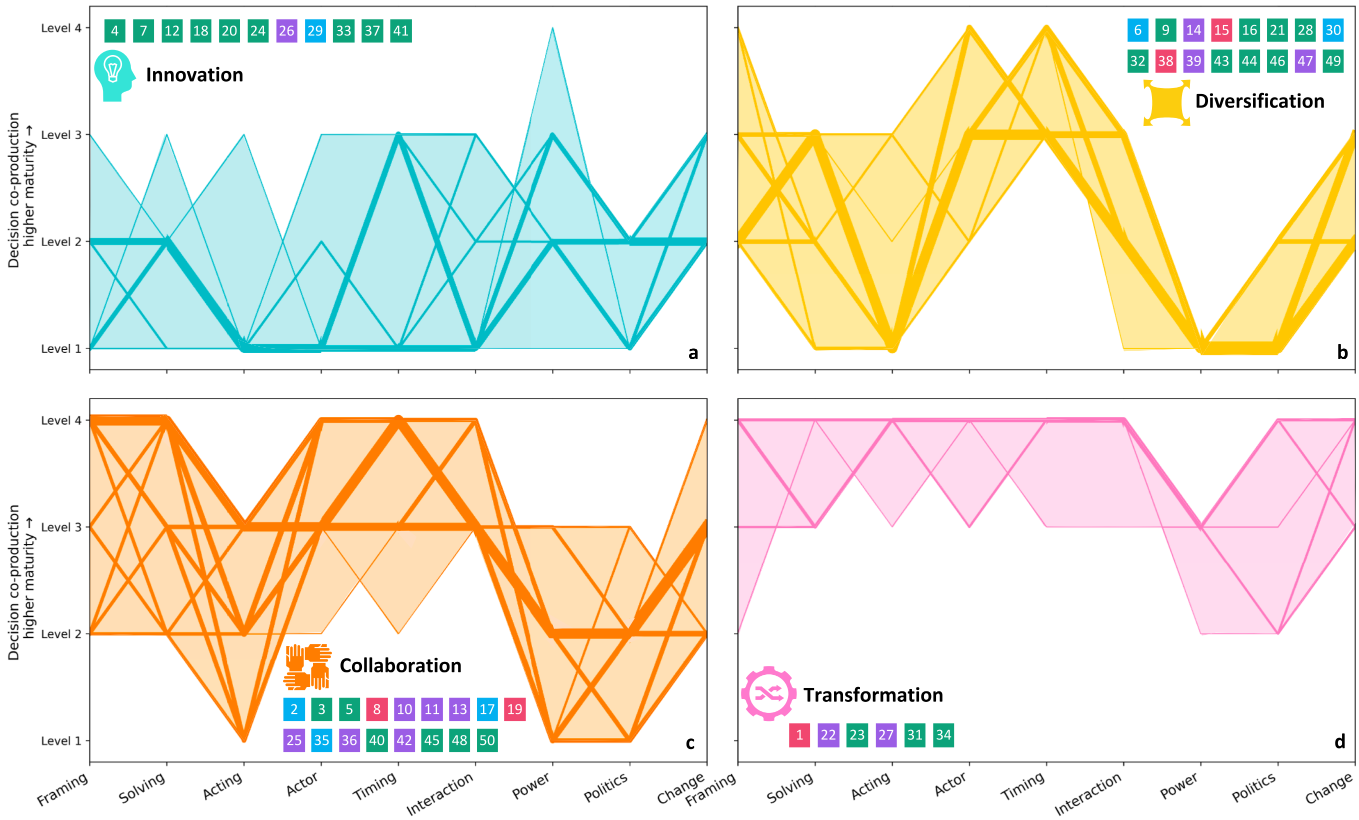

Fig. 3. Characterising the cases against the nine features and the resulting four clusters of decision co-production strategies that emerge from the similarity of the cases. The strategies emerged based on the similarity of cases across nine features related to Motivation (i.e., Framing, Solving, Acting), Setting (i.e., Actor, Timing, Interaction), and Impact (i.e., Power, Politics, Change) using content analysis and clustering (Section 2). In each subplot, the lines represent the cases, the line thickness indicates the number of cases, and the shades between lines show the range of variation. Cases in each strategy are shown in the subplots with boxed numbers that are further detailed in Fig. 1. Icons by Nikita Kozin, Kemesh Maharjan, ProSymbols, and Nithinan Tatah from the Noun Project under a Creative Commons License CC BY 3.0.

3. Charactering key strategies in decision co-production

Despite the uniqueness and diversity of the cases reviewed, our results show that general clusters of strategies for decision co-production emerge from the similarity of the cases across nine features (Fig. 3). These clusters indicate four distinct strategies focusing on *Innovation* in developing and adopting methodological advances; *Diversification* in working across systems and locations to engage with people's world view and policy experience; *Collaboration* in enabling genuine participation; and *Transformation* in thinking through and guiding change on the ground. These four strategies show different extents and ways of working with societal actors, each with strengths and limitations, underpinning high-quality co-production in the context of decision-making under uncertainty. Specifically, we suggest that none of these strategies in isolation would be enough, and collaborative processes in support of decisions under uncertainty should benefit from all of them, tailored to the context of different cases, to maximise effective co-production practices. We explore these key strategies and highlight their nuances with reference to cases in the following.

Innovation. The first strategy, seen in 22% of the cases, is focused on the development and testing of innovative methods for more robust and equitable decisions (Fig. 4). 82% of the cases that share this strategy seek to address the complexity of working with societal actors in decision-making mostly by harnessing advances in quantitative computational experimentation (e.g., objective trade-offs (Herman et al., 2014), conflict resolution (Gold et al., 2019), equity between actors (Jafino et al., 2021a)). Most (82%) of these cases are focused on problems related to water and agriculture, but their innovative analytical methods are flexible enough in other sectors for similar problems, such as long-term infrastructure investment (Trindade et al., 2019), trade-offs between conflicting planning objectives (Herman et al., 2014), and tensions between multiple worldviews (Lempert and Turner, 2021). The common interest in methodological innovation among these cases occurs along with other commonalities related to funding support (91% from national science programs) and contributors (91% involving university researchers).

Cases with a focus on Innovation mostly work with societal actors to inform decision framing, such as defining conflicting policy objectives (Jittrapirom et al., 2018), future uncertainties (Quinn et al., 2020), and alternative performance metrics (Herman et al., 2014). There is less evidence of engagement for acting and implementation of decisions among these cases (Fig. 3a). The Innovation cases also often remain limited to eliciting information rather than facilitating knowledge exchange. This can be in the form of eliciting technical expertise from selected elite groups (e.g., researchers, domain experts/practitioners (Turnhout et al., 2020)) to inform powerful actors with significant control over outcomes (e.g., policymakers, funders). Such a narrow focus may come at the cost of marginalising diversified interests of broader societal actors (e.g., local community, advocacy groups), and, therefore, may limit opportunities for social learning and co-production from the bottom-up (Szetey et al., 2021b).

The cases that focus on Innovation are strong in some aspects of thinking through impact. They enable the exploration of the complexity of actor relationships (i.e., power) with new analytical tools and therefore contribute significantly to the understanding of power dynamics, for example through identifying winners and losers (Jafino et al.,

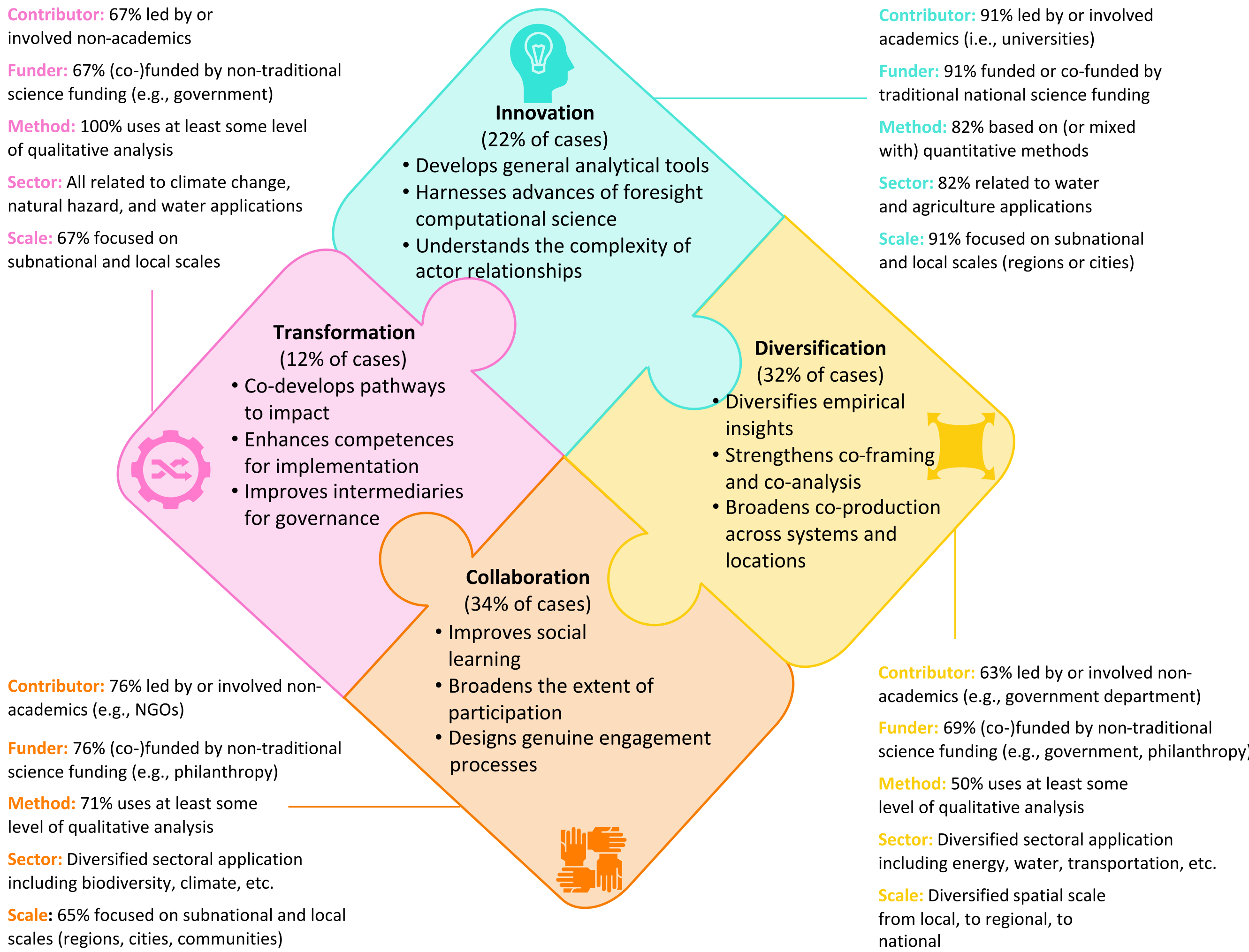

Fig. 4. The key area of focus in four strategies for decision co-production. Decision co-production in human-natural systems should be novel and open to new approaches (i.e., Innovation), applied across systems (i.e., Diversification), collaborative (i.e., Collaboration), and guided towards creating change on the ground (i.e., Transformation). These four strategies, observed and repeated across 50 cases, together underpin high quality decision co-production.

2021a), making actionable compromises (Gold et al., 2019), among others. However, most of them discuss the politics of managing these actor relationships and their governance towards change only in limited ways (Fig. 3a).

Diversification. The second strategy, seen in 32% of the cases, is focused on broadening the span of co-production with actors across systems (e.g., natural disaster, energy, water, sustainable development, climate change), scales (e.g., local, national, transnational), and locations (Fig. 4). While these cases do not often contribute new analytical tools (as with Innovation), they make important contributions by applying the idea of decision co-production in real-world problems and broadening empirical insights across cases for diverse human-natural systems. These cases' broader interest coincides with their less traditional source of funding and their more diverse team of contributors. For example, 69% are co-funded by beyond national science programs (e.g., via philanthropy, international organisations, government departments) and 63% involve organisations beyond universities (e.g., government, independent thinktanks).

Cases featuring Diversification work with societal actors for decision framing and analysis, such as priority setting (Bandari et al., 2021), policy sensitivity analysis (Hurford et al., 2020), risk assessment (Taner et al., 2019), among others (Fig. 3b). Actors are usually closely engaged from the early stages to navigate different views and create a space for deliberation among actors (e.g., via project inception and problem-solving workshops (Taner et al., 2019)). Unlike the Innovation strategy, co-production in the Diversification cases extends beyond eliciting information and is supported by efforts to understand differences and facilitate the exchange of knowledge with a wider range of experts, decision-makers, and citizens in the community (e.g., using visual analysis plots (Hurford et al., 2020), the Chatham House rule (Dessai et al., 2018), brainstorming (You et al., 2014)).

Despite the significance of the Diversification cases in contributing to a wide range of applications, most of them have a limited discussion of how to create impact on the ground (Fig. 3b). They mostly focus on theorising or informing policy (e.g., via better understanding system complexity (Bandari et al., 2021), performance under uncertainty (Lempert et al., 2020)) to influence powerful actors (e.g., investment decision-makers (Sriver et al., 2018), planners and managers (Procter et al., 2017)). There is also typically little or no discussion of the politics and how to enable transformative change through broader empowerment of societal actors (Fig. 3b).

Collaboration. The third strategy, seen in 34% of the cases, is focused on fostering social learning and inclusive and genuine participation (Fig. 4). The cases that focus on Collaboration are important and unique for their strong emphasis on designing processes to understand disagreements, identify the common ground through negotiation, and embrace plurality of perspectives (not necessarily aiming for consensus). The cases that share this strategy are distinct from others in their dominant focus on managing systems at smaller scales with higher social cohesion (i.e., 65% on regions, cities, and communities) – a suitable

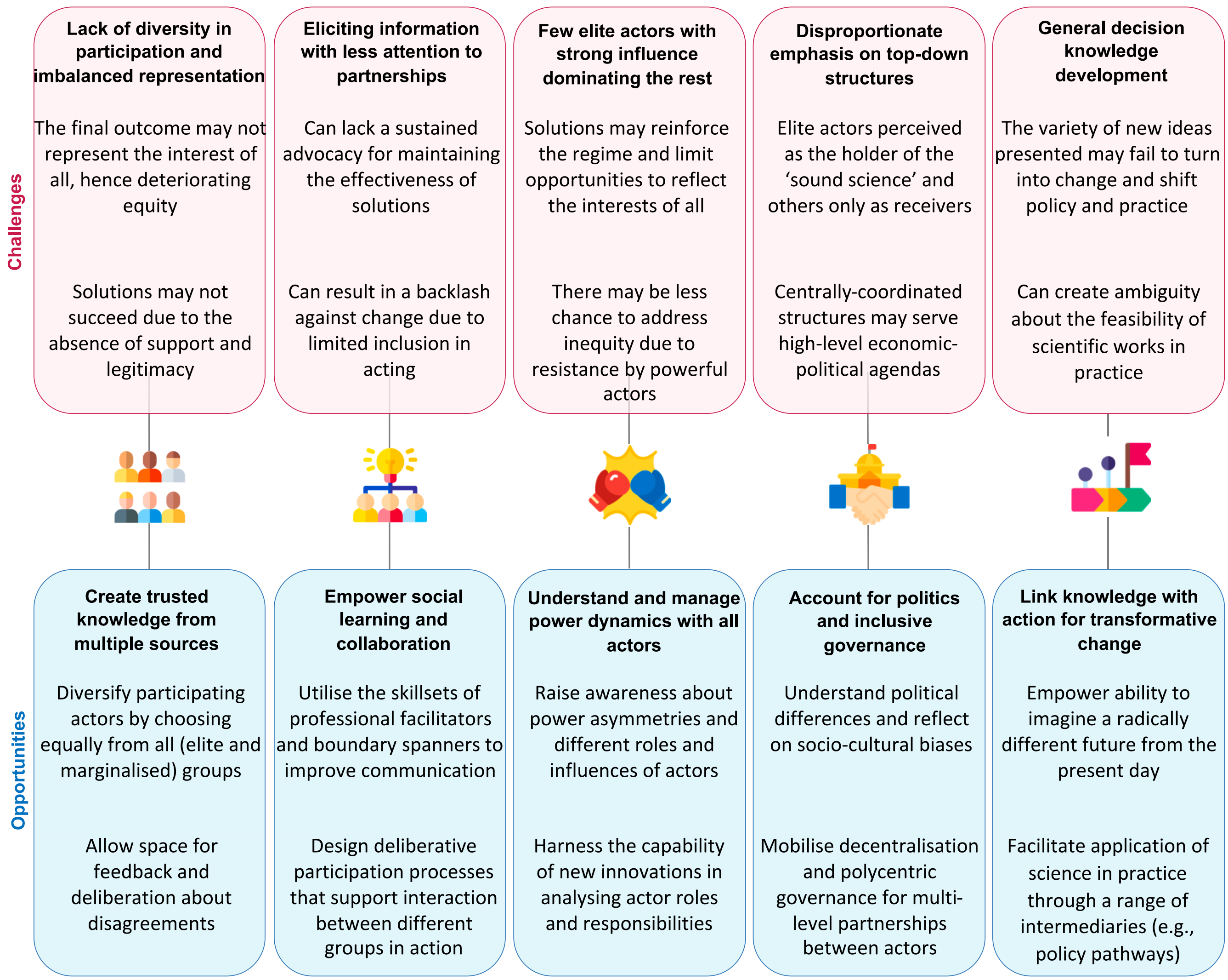

Fig. 5. Examples of challenges and opportunities in decision co-production. They are synthesised across the cases and shared among the identified decision co-production strategies (see Methods in subsection 2.4). Icons by Freepik and Smashicons from https://www.Flaticon.com under free personal and commercial license with attribution.

feature to leverage engagement and co-production with actors. Employing a mix of methods from social science, action research, and decision analytics, 71% of these cases involve some form of qualitative transdisciplinary analysis. The higher transdisciplinary interest in these cases coincides with their other commonalities related to a mix of funding sources and a more diverse team of contributors. For example, 76% are co-funded by non-traditional sources such as philanthropy and NGOs and 76% involve non-academic.

The Collaboration cases broaden the extent of participation to represent wider actor groups beyond elites and include voices that are often marginalised (e.g., citizens, advocacy groups (Bojórquez-Tapia et al., 2021; Neina et al., 2018), local communities (Szetey et al., 2021a)) (Fig. 3c). They also deepen the nature of participation to promote co-learning to ensure actors can learn from each other (Gebrehiwot and Zurek, 2018), reflect on their perspectives (Malekpour et al., 2017), and co-design with other actors to improve the ownership of the results (Szetey et al., 2021a). The inclusive participation across the Collaboration cases is reflected throughout the decision process. These include participation from early steps to ascertain the shared aspirations and normative views (Szetey et al., 2021a), to intermediary steps to analyse the drivers and barriers (Malekpour et al., 2017), to final steps to validate and modify key findings based on actors' feedback (Bojórquez-Tapia et al., 2021). The intensive and genuine participation may minimise the risk of marginalising people, ensure all voices are heard, and build trust and confidence in the process and outcomes.

Collaboration cases address some of the limitations discussed in the previous strategies (Fig. 3c). These cases start to discuss the role of societal actors in implementation settings, for example by proposing detailed action plans (Groves et al., 2020; Molina-Perez et al., 2019). The cases also bring a more explicit understanding of power relationships among actors, for example by discussing corrective/empowering interventions for power imbalances (Gebrehiwot and Zurek, 2018; Neina et al., 2018). They also discuss how to work with different actors, for example through influencing powerful actors (Bojórquez-Tapia et al., 2021; Hu et al., 2019), empowering marginalised groups (Kwenye et al., 2018; Szetey et al., 2022), among others. While Collaboration cases co-produce knowledge to inform policy for change (e.g., advising governments on plans (Benavides et al., 2021)), often they do not discuss how to co-manage transformation on the ground with societal actors (Fig. 3c).

Transformation. The fourth strategy, seen in 12% of cases, is focused on thinking through change, guiding effective implementation, and designing pathways to impact, as the outcomes of the collaboration (Fig. 4). The cases that share this strategy often design participatory approaches that can potentially integrate people's knowledge and policy experience throughout the key stages of managing human-natural

Box 1
Developing a robust urban water strategy with stakeholders in Mexico

To meet growing demand for water in Monterrey, Mexico, the country's third-largest metropolitan area, in 2010, state authorities proposed the development the Pánuco Aqueduct project, a 370 km long water conveyance facility from Veracruz, a less developed state in the south of Mexico (Molina-Perez et al., 2019). The project was the source of significant controversy. Partly in response to this controversy, the water policy community of Monterrey decided to develop the region's first long-term water plan (the Monterrey Water Plan [MWP]) in 2016.

Through the application of decision-making under deep uncertainty, researchers conducted a study that evaluated the vulnerabilities of Monterrey's water management system to future climate and technological change and demand uncertainty. Working collaboratively with the water policy community of the city, the study team developed an adaptive strategy designed to minimise vulnerabilities at an acceptable cost.

For scoping the analysis, the research team held three workshops with a variety of stakeholders, including state and federal agencies, private companies, NGOs, academic institutions, and the public water-utility company in Nuevo León, to discuss the study's purpose, identify the key uncertainties and candidate water management options, and set performance metrics (Fig. 6). In subsequent interactions with stakeholders, the research team shared study findings via interactive tools and plenary discussions which were used to validate, expand, and refine the analysis in response to specific stakeholder input.

The outcome was a robust, adaptive strategy for Monterrey that took the full advantage of the options available in the basin (Fig. 6). It analysed a set of broadly diversified alternatives proposed by the water policy community and identified economically and politically feasible policy portfolios that included: a) no-regret, near-term actions that minimise cost while meeting reliability objectives; and b) adaption options for different conditions in the future that warrant the plan can succeed in the long-term. The study impacted policy design and implementation in Monterrey, avoiding a high-cost and risky basin-transfer project in favor of a lower-cost, no-regret strategy that was co-developed with the local water planning community.

systems. Examples include the joint framing of priorities and options (Lawrence and Haasnoot, 2017), interactive problem solving (Bhave et al., 2018), and collaborative implementation (Hebinck et al., forthcoming) and monitoring (Haasnoot et al., 2018). Co-production is achieved through sustained and meaningful dialogues with societal actors, including citizens, local/Indigenous communities, and policymakers, so that decisions about important issues can be made jointly with others.

To design pathways to impact, the cases featuring Transformation open the black box of power and provide a moderate understanding of actor agency, their relationships, and barriers to their action (Fig. 3d) (e.g., via gaming (Lawrence and Haasnoot, 2017)). With an improved understanding of power, alternative routes can be designed in response to potential barriers (Roelich and Giesekam, 2019). An improved understanding of power and agency can also lead to more insights into the diversity of actors' expectations and their bottom-lines, facilitate negotiation and compromises among conflicting expectations, and coordinate necessary actions to support improved interaction. Compared to other strategies, Transformation cases can improve governance capacity by distributing responsibilities between actors (Bhave et al., 2018; Lawrence et al., 2019; Roelich and Giesekam, 2019). They can also better enable change by providing a range of intermediary tools, such as pathway development, monitoring, and contingency planning tools (Haasnoot et al., 2013; Haasnoot et al., 2018).

4. Towards flourishing co-production in decision support

Individual strategies in isolation, each with certain limitations and strengths in various contexts, cannot lead to high-quality decision co-production, and therefore none of the discussed cases necessarily represent the "best" or the "ideal" strategy for every case of decision co-production. Rather, co-production in decision-making needs to be underpinned by learning from and integrating the most constructive and complementary features of all four strategies, in a way suitable for the context and intended objectives of projects. We explain what these general strategies can learn from one another by discussing some of their main *challenges* and *opportunities* (Fig. 5), drawing on several best-practice examples from our selected cases and beyond. The purpose of discussing challenges and opportunities here is not to be fully encompassing, but rather to focus on those characterising features that were less developed in our results (i.e., Actor, Acting, Power, Politics, Change) to highlight important deficits and exemplify promising ways to improve co-production in decision support.

4.1. From limited to balanced representation of actor diversity

Managing human-natural systems requires approaches beyond technical solutions, and should involve the knowledge of different people (e.g., needs, capacities, cultural values, hidden preferences) to increase the chance of success (Smajgl and Ward, 2015). However, the knowledge source in some of the cases analysed is not discussed explicitly or is dominated by domain experts often with high levels of interest and power (e.g., 91% of the Innovation cases were at Levels 1 or 2 of the Actor axis in Fig. 3a). This results in biases in understanding and compromises which may not represent the interests of all societal actors, hence deteriorating equity. It also results in solutions which may not succeed due to the absence of support and legitimacy.

Addressing this challenge requires broadening the source of knowledge by respecting and incorporating multiple ways of knowing and engaging with diverse actor groups; not only elite actors (e.g., government bodies, technocrats, scientists, large NGOs) with high power and influence, but also those who are marginalised such as local and Indigenous communities, and small businesses/NGOs. Diversifying actors creates the opportunity for input from other actor groups, likely increasing willingness to adopt proposed solutions (asserted as a factor of project success on the ground (Nikas et al., 2022)), potentially leading to more legitimate, credible, and relevant outcomes (Dawson et al., 2021). This also enables the questioning of dominant agendas, and the elevation of diverse and marginalised opinions that are often overlooked when efforts are not made to deliberately include them (Chambers et al., 2021). When the context involves Indigenous communities, decision co-production and engaging with these communities becomes critical to ensure mutual respect of multiple traditional and non-traditional views, as was observed in engaging with three Indigenous communities in a case of decision-making for coastal management in New Zealand's North Island (Lawrence et al., 2019). Stakeholder analysis tools and novel engagement processes are emerging that can help diversify sources of knowledge, ensuring marginalised actors are represented and their voices are being heard as much as those with high power (Ningrum et al., 2022; Reed et al., 2009).

There are common risks in working with diversified actor groups. For example, disagreements may arise, particularly if the discussion is on controversial or polarising issues. The disagreements can often be

Box 2
Participatory scenario development to assess trade-offs in African Agriculture

The Sentinel research project (2017-2021) hosted three participatory scenario development workshops in Ghana, Ethiopia, and Zambia in 2018 to map the crucial trade-offs and synergies in the agricultural system in a co-creative manner and co-create pathways to address these (Gebrehiwot and Zurek, 2018; Kwenye et al., 2018; Neina et al., 2018).

The 3-day workshops took place in or close to the capitals of Ghana, Ethiopia, and Zambia (Fig. 7). Around 25-30 local stakeholders from policy, the private sector, NGOs, and academia participated in the workshops, which were facilitated by 3-4 researchers from the local partner university and 3-4 project-researchers from the UK. Most participants did not have previous experience with foresight or scenario development. The participation of diverse actors meant different experiences and knowledges about agricultural development were part of the co-creation. In addition, the use of a future perspective was empowering, as it allowed the participants to think beyond the constraints and power dynamics that are embedded in today's systems (Hebinck et al., 2018). These elements were vital for identification of scenarios which were sophisticated and complexity in terms of scales and system relations. They were also important for the identification of trade-offs as what constitutes a trade-off depends on a person's knowledge, need, values, and beliefs.

A brief analysis of key dynamics in the agricultural system and major policy developments kick-started the workshops. This was followed by group exercises to frame a desirable future, identify key challenges to realising that future, and discuss what drives these futures. In plenary, participants then discussed and negotiated the ranking of drivers to identify those most crucial to the system. The two indirect drivers that were identified as the most important were used as the basis for four diverse and plausible future scenarios. The group then used backcasting methods to co-create a pathway from the present to realise each scenario for 2050. The participants finally shared insights, compared pathways, and discussed the trade-offs and synergies that emerged from the work.

addressed by allowing space for feedback and deliberation, as was observed in a case of flood control management in Shanghai, China to resolve contested stakeholder priorities (Hu et al., 2019). In most circumstances, actors can resolve differences of opinion among themselves and come to an amicable solution. For those that cannot, the ability to hear opposing views is still valuable, as it sparks an ongoing process of discussion and understanding which can potentially be continued beyond the decision-making process (Szetey et al., 2021a).

The unwillingness of actors to engage is another risk (Smajgl and Ward, 2015), which often requires designing participation (e.g., prioritising when to approach actors throughout the process and for what type of knowledge (Uittenbroek et al., 2019)) in a way that minimises engagement fatigue. Here, thoughtful design of co-production processes is important to enable constructive interaction of the process with the socio-cultural context, which in turn may prevent destructive disagreement before it occurs (Moallemi et al., 2021; Wyborn et al., 2019). An example of constructive interaction with diverse actors was the case of national decarbonisation in Costa Rica where the research team developed and used interactive tools to support discussions with diverse stakeholders of more than 50 of Costa Rica's government agencies, industries, and NGOs (Groves et al., 2020). Another similar experience was in the case of robust planning for urban water management in Monterrey, Mexico (Molina-Perez et al., 2019) where inputs from diverse actor groups were incorporated in decision-making through problem framing workshops to have a more comprehensive view of the water system's vulnerabilities under future climate uncertainties (Box 1).

4.2. From information elicitation to collaborative action

Within a context with actor diversity, collaborative action is about how to ensure we incorporate the plurality of different human values and perspectives throughout the decision-making process and create successful collaborations. This means engaging with actors not only for eliciting preferences and informing methodologies, but also for acting on resulting decisions with people who have a deeper understanding of human complexities in practice and better know the embeddedness of proposed solutions in the society's cultural and institutional settings (Avelino, 2021). Despite this, most cases describe little or no collaboration for acting on decisions (e.g., 91% and 88% of Innovation and Diversification cases respectively were at Levels 1 or 2 of the Acting axis in Fig. 3a and 3b). This is an important gap for maintaining the effectiveness of decisions as actors support and implement solutions in long-term if they can see the relevance in terms of social identities and cultural traditions (Chabay et al., 2021). The limited inclusion of actors in enacting decisions may also promote scepticism and damage the sense of ownership, resulting in a backlash against change (Morrison et al., 2015).

The first step is to create the capacity for collaborative action. One way to create this capacity is through improving communications with a common language (whether that be eliminating jargon, or using different languages) that spans the boundary between different groups, as discussed theoretically (Moser, 2016; Zare et al., 2020) and also experienced in practice (e.g., in workshop design for carbon neutrality planning in Chile (Benavides et al., 2021)). An opportunity to improve communication is to utilise the skillsets of individual intermediaries (e.g., engagement facilitators, community-based liaisons) that can foster the links between analysis and action (de Kraker, 2017), commonly referred to as boundary spanners (Bednarek et al., 2018) or knowledge brokers (Miller et al., 2014). Boundary spanners can help with designing deliberative processes for interacting with different groups based on an understanding of power and type of information suitable for each group to bridge the distance between the research team and the community and create trust and a sense of ownership of the outcomes (Kivimaa et al., 2019; Moss et al., 2021). Examples are the two cases of local, community-driven sustainability planning in southern Australia where collaboration with professional facilitators (some with existing connections to local stakeholders) and workshop consultants resulted in higher willingness for participation among the local communities and more effective outcomes for the research team (Bandari et al., 2021; Szetey et al., 2021b).

There are a range of other participatory tools that can offer different levels of analytical capability and build the capacity to collaboratively act on decisions (Lynam et al., 2007). Those that are more qualitative (e.g., workshops, gamification) are useful for a deeper understanding and conceptual framing of priorities and solutions. For example, narratives as an effective communicative mechanism can reflect culture-specific perceptions, societal values, and human preferences through storylines and facilitate dialogue between actors (Chabay, 2020). A related case is that of regional climate adaption planning in Karnataka, southern India where narratives played an important role in communicating local risk assessments and adaptation decisions, and in creating a better understanding of complex interactions of climate processes and anthropogenic factors for acting on the ground (Dessai et al., 2018).

Other participatory approaches such as multi-stakeholder foresighting have been used to identify trade-offs and synergies scenarios for agricultural development in three African nations, which have built up expectations and co-produced insights on major challenges and pathways to the future in a collaborative manner (Kwenye et al., 2018) (Box 2). Advances in computational science are also emerging that complement qualitative tools by consolidating human perspectives into formalised or measurable knowledge for greater clarity in framing the problem (Lempert and Turner, 2021), experimenting with solutions (Hadjimichael et al., 2020), and finding relevant compromises when human perspectives are in conflict (Gold et al., 2019), all of which can improve a shared understanding among actors and later facilitate collaboration for acting on the ground.

4.3. From 'power over' to 'power with' actors

Understanding power dynamics and ensuring reciprocity underpin efforts to manage conflicts and cooperation between actors and can enable redistribution of access to resources (e.g., infrastructures, technologies). They are also necessary to shifting power imbalances (Avelino, 2021). However, power is not yet sufficiently addressed in support of decision-making under uncertainty where most cases have little or no understanding of it (e.g., 100% and 82% of Diversification and Collaboration cases respectively were at Levels 1 or 2 of the Power axis in Fig. 3b and 3c). Among the cases, elite actors with more power (e.g., government, industry, large NGOs) or a strong authority from their scientific expertise (e.g., scientists, technocrats) often have disproportionate influence. Their higher influence can potentially lead to outcomes that reinforce established regimes and limit opportunities for compromises that reflect the interests of all. It can also exacerbate existing inequities among those highly affected by the imposition of outcomes but who are relatively powerless in policy decisions (Wyborn et al., 2019).

Confronting asymmetries and providing opportunities to those with a lived experience of inequity (e.g., underserved regions, Indigenous communities) to take part is important (Pereira et al., 2020) to shift the discourse from 'power over' (i.e., some actors are dominated by others) to 'power with' (i.e., all actors are empowered and contribute) (Avelino, 2021). An example is a case of power-sensitive conservation management in the Gulf of Ulloa, Mexico that addressed asymmetries through facilitating a sensible and respectful debate between government, the fishery industry, and environmental agencies and break the deadlock in policymaking (Bojórquez-Tapia et al., 2021). Diversified funding sources and contributors can provide new motivation to focus much more keenly on social elements and engage with underrepresented groups (Mitchell et al., 2015). Shaping horizontal and non-hierarchical interactions can also help ease political and social pressures on actors, thereby encouraging marginalised groups to participate and reducing power asymmetries (Turnhout et al., 2020).

Various examples from the literature examining decision co-production have highlighted the importance of making power explicit by analysing actor roles and responsibilities. Raising awareness about the agency of actors (e.g., understanding different roles and influences) is a modest way to make power explicit, so that additional measures can be taken to address constraints in rebalancing power. This was advocated for in the case of climate change mitigation in the construction sector in the UK, showing the importance of alignment between different agencies when developing plans and building momentum for radical change (Roelich and Giesekam, 2019). Participatory foresighting approaches are also helpful in empowering people to think beyond the constraints and power dynamics of today's systems, as was observed in the case of participatory scenario development for agriculture in Africa (Kwenye et al., 2018) (Box 2).

Complex contexts, with conflicting priorities and solutions that affect various actor groups in different ways, may require methods of higher analytical capability. Recent methodological advances in data analytics have emerged to map complex power relationships (Gold et al., 2022), evaluate equity between actors (Jafino et al., 2021b), and explain potential cooperation and conflicts, which have not been fully exploited in practice. For example, in North Carolina in the US, in a context full of conflicting objectives between powerful neighbouring urban water utilities, computational optimisation tools were used to map power relationships and find actionable compromises between regional cooperating partners in addressing the challenges of water scarcity and population growth (Gold et al., 2019). Similarly, other methods (e.g., actor-linkage metrics, social network analysis) can help understand power relationships in efforts to build, shift, or influence power asymmetries (Gaventa, 2006). Combining these advances in future co-production projects can offer opportunities for addressing some of the current challenges.

4.4. From top-down structures to inclusive politics and governance

Politics as the act of deciding who does what, when, and how is a key factor in connecting science with policy and action to affect change (Lasswell, 1936). However, the inherently politicised nature of science-society relationships is largely undiscussed among the analysed cases (e.g., 100% of Innovation and Diversification cases were at Levels 1 or 2 of the Politics axis in Fig. 3a and 3b). A risk of underrepresenting politics is that decisions may be made primarily by elite actors who are the holders of knowledge, while others are cast as receivers whose perspectives should be corrected by scientific expertise, hence discouraging co-production (Turnhout, 2018; Wyborn et al., 2019). Additionally, there is the risk that the expert argument being represented as 'sound science' (i.e., universal/best answer to the problem) with a particular favoured direction of change, forces people to fit into expert rational paradigms (Stirling, 2010; Turnhout et al., 2020).

Different ways have been suggested to improve the focus on politics and enhance the democratic quality of working with societal actors (Turnhout et al., 2010). For example, some studies highlight the importance of making the right connections between scientists, people, and policymakers to improve inclusivity and reflect on socio-cultural biases that could potentially lead to the disengagement of certain political interests (Blythe et al., 2017; Klenk, 2018). Careful design of co-production processes to fit the context is of critical importance to navigating the boundary between politics and science. Science and technology studies (STS) literature has provided coherent theoretical frameworks to conceptualise science, politics, and society and provided practical guidance on how to ensure that processes are designed to "open up" rather than "close down" on these priorities (Beck et al., 2021; Stirling, 2007; Stirling, 2010). Another example from STS is Jasanoff (2010) who demonstrates the problematic separation of science from society in the context of climate change and explores the perceived polarity of scientific facts and the human experience of climate change. Further engagement with this literature is needed to avoid erroneous 'one-track' pathways and enable plural policy debate with a more equal partnership between social and natural science.

Governance, as arrangements to manage common affairs and act on decisions within a political system, is also commonly seen in our case studies to be top-down (Biermann, 2007; Biermann et al., 2017). This means that implementing plans and programs is centrally coordinated, with those who govern holding the most responsibility and imposing direction upon the rest of the actors. Centrally coordinated governance arrangements may also result in disproportionately serving high-level economic-political agendas and be insensitive to nuanced local issues. However, this does not have to be the case. Governance can be more inclusive as actors can have strong connection to place and hold the local knowledge needed to develop place-based innovative solutions (Manzo and Perkins, 2006).

Suggestions have been made for working towards more inclusive governance with stronger emphasis on actors at the local scale and

Box 3
Downscaling global sustainability goals to the community level in Australia

Forrest is a small regional town in southern Australia. The community has a strong forestry and agricultural history but has had to pivot to new economic sectors (particularly tourism) after the banning of logging in the local area in 2008. The people in Forrest have different views about their community's future sustainability now and into the future as they transition. Szetey et al. (2021b) used the global SDG framework as a template and worked closely with the community to find pathways to a subset of sustainability priorities under uncertainty, using local knowledge and by the people who live there.

To discover local community priorities, a range of community engagement activities was organised (Fig. 8). These began quite broadly: asking people on the street which SDGs were most important for the community, using only the SDG icons as a guide. Other activities included guided discussions with groups of locals, selected for diversity of opinion and experience by a local collaborator to understand the joys and frustrations of living in the town. An independent desktop-based content analysis of locally relevant documents (e.g., newspapers, policy reports) was also conducted to identify the SDGs which were most commonly referenced. Using all this information, a subset of SDGs was selected that were most relevant for the community. They were synthesised into a document called the Forrest and District Plan, showing the sustainability priorities in broad themes and in relation to the major driving forces for change in an uncertain future with a horizon of 2030 (Fig. 8). This plan contained not only the locally important SDGs, but also community-sourced ideas for ways and arrangements in which to improve the town (chiefly by way of infrastructure improvement) in order to achieve the goals. This process of co-production was considered locally as a roadmap representing collective community aspirations and solution ideas for their sustainable future – a guide for progress in Forrest through the exercise of an inclusive, bottom-up governance process.

The synthesis of the community's sustainability goals and ways to achieve them in a participatory process enabled both the community and those who interact with them (be it government or non-government organisations) to understand the place which the community is aiming to reach. This gave the community a platform from which to advocate for their own sustainable development, based in the SDGs. Beyond this, the deep participatory and collaborative nature of the prioritisation process gave the identified goals legitimacy and a sense of ownership that can keep the community motivated in pursuing them.

grassroots initiatives. For example, decentralisation and polycentric governance have been mentioned as an avenue for partnerships across (especially local) scales that also involve many actor groups in inclusive and non-hierarchical ways (Biermann, 2007; Morrison et al., 2019; Romsdahl et al., 2018). Governance at the local scale may arise organically through the need to manage common resources. It can be devolved to a community from higher levels of formal government, or in response to the devolution of responsibility from higher levels of government, eventually resulting in benefits for credibility, adaptiveness, and inclusivity (Moallemi et al., 2019). The use of multi-dimensional frameworks such as the Sustainable Development Goals (SDGs) can also help manage interacting governance groups across scales, and structure their desired outcomes within the context of a more broadly accepted and understood framework (Szetey et al., 2021b). An example of this is a case of local planning in a small community in southern Australia which adopted a local lens and used the SDGs as a framework to enable bottom-up governance (Szetey et al., 2021a, b) (Box 3).

4.5. From general knowledge to thinking through change

It is broadly acknowledged that catalysing societal and policy transformation is a crucial component in managing human-natural systems (Sachs et al., 2019), yet most of the cases focus on scientific recommendations and do not specifically think through change in terms of understanding barriers to reform and to transform (e.g., 73% and 56% of Innovation and Diversification cases respectively were at Levels 1 and 2 of the Change axis in Fig. 3a and 3b). This can lead to failure in turning ideas into concrete actions for impact and can create ambiguity about their feasibility in practice.

Addressing the gap with respect to change requires further work on spanning the boundary between knowledge systems and the realm of action (Cash et al., 2003). Alternative ways have been offered to improve this link. One is by improving thinking through change among people and policymakers, i.e., their ability to imagine a radically different future and co-design pathways to achieve this future. Different types of participatory activities can be used to employ some form of visioning, scenario, and pathway development (Jasanoff and Kim, 2015). There is no single 'right' way to the future, and there are multiple alternative pathways rooted in the context of each problem (Schneider et al., 2019a). The diversity of local conditions can lead to numerous opportunities in the pursuit of change (Moallemi et al., 2021; Pereira et al., 2020). By engaging with societal actors, pathways become inclusive processes that use human knowledge to inform change towards imaginative and anticipatory futures (Hebinck et al., 2018; Muiderman et al., 2022).

Other studies suggest that the missing link between engaging with societal actors in science and creating real world transformation is driven by the dominant view of science in a political context in its traditional role of theorising and advising (rather than enabling change (Hajer, 2012; Kowalczewska and Behagel, 2019)). Hence, these studies highlight that the process of integrating actors should become part of the broader political agenda to shift this dominant view (Turnhout et al., 2020). This conclusion is shared by other contributions to the literature which synthesise aspects of co-production and could be said to be the principal motivation for the use of knowledge co-production in science to support decision-making (Bandola-Gill et al., 2022; Chambers et al., 2022; Wyborn et al., 2019).

There are also other approaches that can facilitate the translation of knowledge in action. Among them is the idea of *policy pathways* (Haasnoot et al., 2013). Sector-specific interventions in silos with no change over time would not be able to address multi-dimensional and constantly evolving problems, and adaptation across interventions is needed over time. Policy pathways provide a range of intermediary concepts and tools to guide how interventions can be implemented and adapted in response to changes in the real world, providing guidance and process recommendations for turning decisions into action (Gold et al., 2022; Hermans et al., 2017; Kwakkel, 2017; Trindade et al., 2020). Their aim is to adjust decisions gradually over time by switching between a manageable number of short-term, low regret, and preparatory measures that are needed for problems requiring immediate attention; and those that are more long-term, irreversible, and transformative that require preparation.

Incorporating monitoring systems in managing human-natural systems is a key component of policy pathways helping with continuous evaluation to improve the process and giving timely and reliable signals to adjust decisions in response to future developments (e.g., defining

Box 4
Co-designing a monitoring system for Delta management in the Netherlands

In 2010, the Dutch government launched the Delta Program to further prepare the Netherlands for climate change and socio-economic development and ensure safety against flooding and the provision of sufficient fresh water. Uncertainty about future climate change complicates the implementation of adaptation decisions and limits their robustness. To address these challenges, the Delta Program, in collaboration with actors from the national government, water boards, city representatives, farmer unions, drinking water companies, and environmental organisations, designed a set of intermediary monitory processes to guide adaptive policy making using adaptation pathway (Bloemen et al., 2019; Haasnoot et al., 2018; Van Alphen, 2016).

To develop the monitoring system, a list of measurable signposts (i.e., indicators that specify information that should be tracked) that could provide timely and reliable signals was discussed and identified in an iterative process between experts of the Signal Group and other actors within the Delta Program (Fig. 9). Signposts were selected that have credibility for actors to act on. When actors were asked to review the monitoring system, it emerged that having an overview and knowledge of the reasons why signposts were selected was also required to build acceptance. To this end, the monitoring system included primary signposts that were required ('need to know') and secondary (explanatory) signposts that could assist analysts to better understand the information obtained ('good to know'). Further discussions with the actors were also focused on how the derived information should be analysed to obtain the relevant information for decision making (e.g., directions for implementing or adjusting decisions).

The iterative process has been enabling pro-active climate adaptation in the Netherlands where forward-looking investments are being made. For example, emerging scientific evidence of accelerated sea level rise in the North Sea is already fostering a public policy debate about speeding up or leapfrogging the implementation of actions on the pathways (Keizer et al., 2022; Steffelbauer et al., 2022). The monitoring system and signal group established also proved effective for incorporating new signals that were not part of the standard signposts (e.g., a pandemic, new societal preferences).

thresholds to trigger the next phase of agreed solutions). One example is the co-design of a monitoring system in the Netherlands' Delta Program to support the implementation of planned interventions against flooding in a way that can improve adaptation decisions on the ground (Haasnoot et al., 2018) (Box 4). There is also a growing number of other research case studies and theoretical frameworks being developed to design and implement policy pathways (Trindade et al., 2020). Institutional connectivity of the proposed pathways, their feasibility, and potential path-dependencies and lock-in effects are among other important components that need deliberation with actors to make sure that the developed pathways can effectively engage with institutional and political context on the ground (Nielsen et al., 2020; Voß and Bornemann, 2011).

5. Conclusions

Despite the rapid development of analytical tools and computational advances in decision-making under uncertainty, the use of human capabilities for decision-making and knowledge co-production has not been systematically defined and remains a topic of lively debate (Glynn et al., 2018; Walker et al., 2018). Our analysis of the 50 cases was a first step to synthesise important lessons from many empirical research collaborations across the world to suggest and demonstrate four alternative strategies for co-producing decisions with people and policymakers. While these identified strategies and their explored features do not form an exhaustive and definitive list, they set out the main pillars for improving decision co-production in research and practice. They also offer an opportunity to learn from previous cases' challenges and suggest ways towards flourishing decision co-production in the future through diversifying trusted knowledge sources, empowering collaboration in action, managing power dynamics, enabling inclusive governance, and facilitating transformative change. Given the empirical support of the 50 cases with diverse co-production characteristics, location, scale, and scope, the synthesised practical lessons should be a good representative of real-world decision-making in human-natural systems under uncertainty. However, we are also aware of potential biases that some of these findings could have to our sample of case studies. Hence, a careful consideration of features in new contexts is important in interpreting and extending our results.

By exploring cases that had different strategies, challenges, and opportunities, we conclude that the question we face is not about what group of cases or which strategy is better than others. We argue that integrating the constructive features of all different strategies is important to navigate transformations in global challenges with complex and uncertain human and policy dimensions. We also recognise that there is no one-size-fits-all template for decision co-production, and cases require fit-for-purpose arrangements to suit different systems, locations, scales, and actors.

CRediT authorship contribution statement

Enayat A. Moallemi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fateme Zare:** Investigation, Formal analysis, Data curation, Writing – review & editing. **Aniek Hebinck:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Katrina Szetey:** Writing – review & editing, Writing – original draft, Investigation. **Edmundo Molina-Perez:** Writing – original draft, Investigation, Formal analysis, Data curation. **Romy L. Zyngier:** Writing – review & editing. **Michalis Hadjikakou:** Writing – review & editing. **Jan Kwakkel:** Writing – review & editing. **Marjolijn Haasnoot:** Writing – review & editing, Data curation. **Kelly K. Miller:** Writing – review & editing. **David G. Groves:** Writing – review & editing. **Peat Leith:** Writing – review & editing. **Brett A. Bryan:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

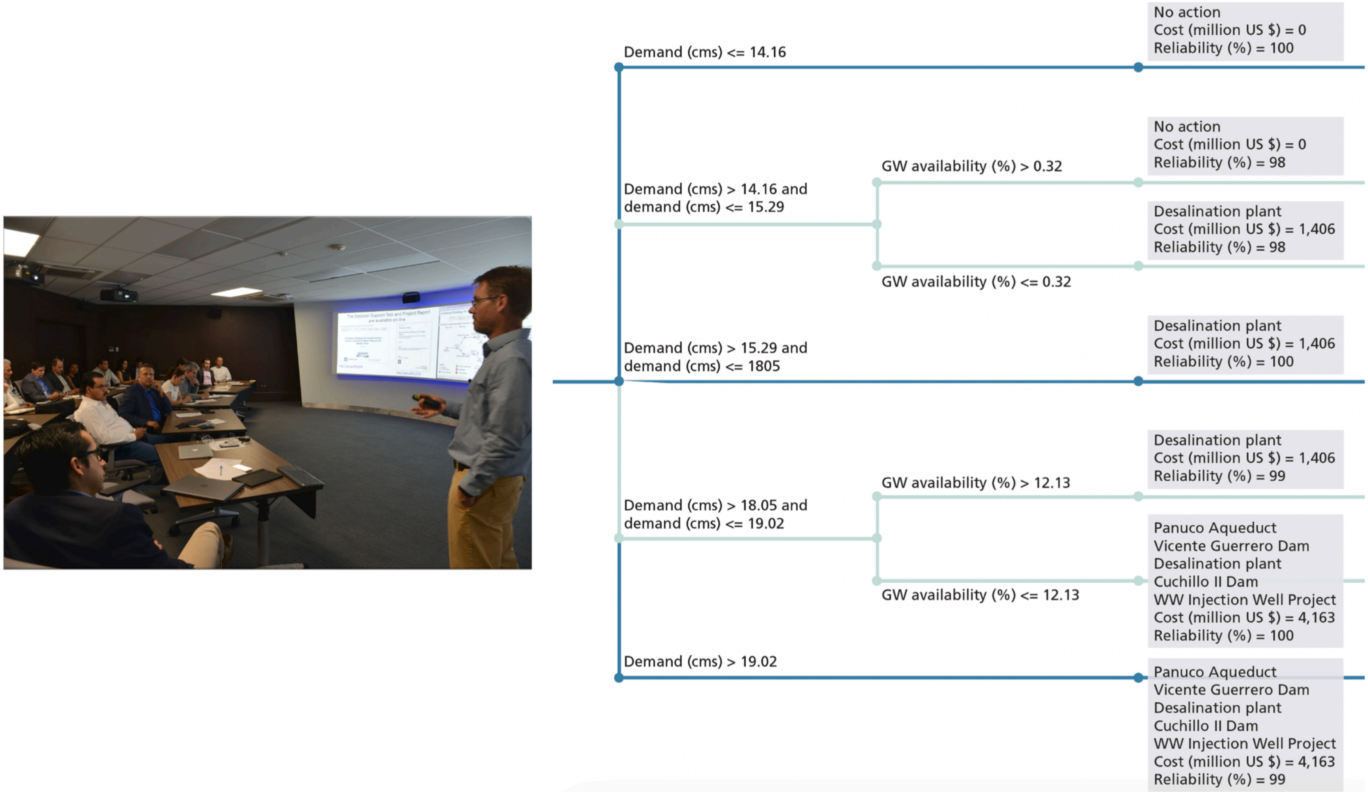

Fig. 6. Participatory urban water robust decision-making. (Left) the decision framing workshop to identify vulnerability conditions, photo credit: Tecnológico de Monterrey. (Right) a simplified version of the decision co-production output, i.e., the adaptive water strategy, see the full version from Molina-Perez et al. (2019). Photo credit: RAND Corporation.

Fig. 7. Participatory scenario development workshops. (Left) workshop in Ghana. (Right) workshop Zambia. Photo credit: Aniek Hebinck.

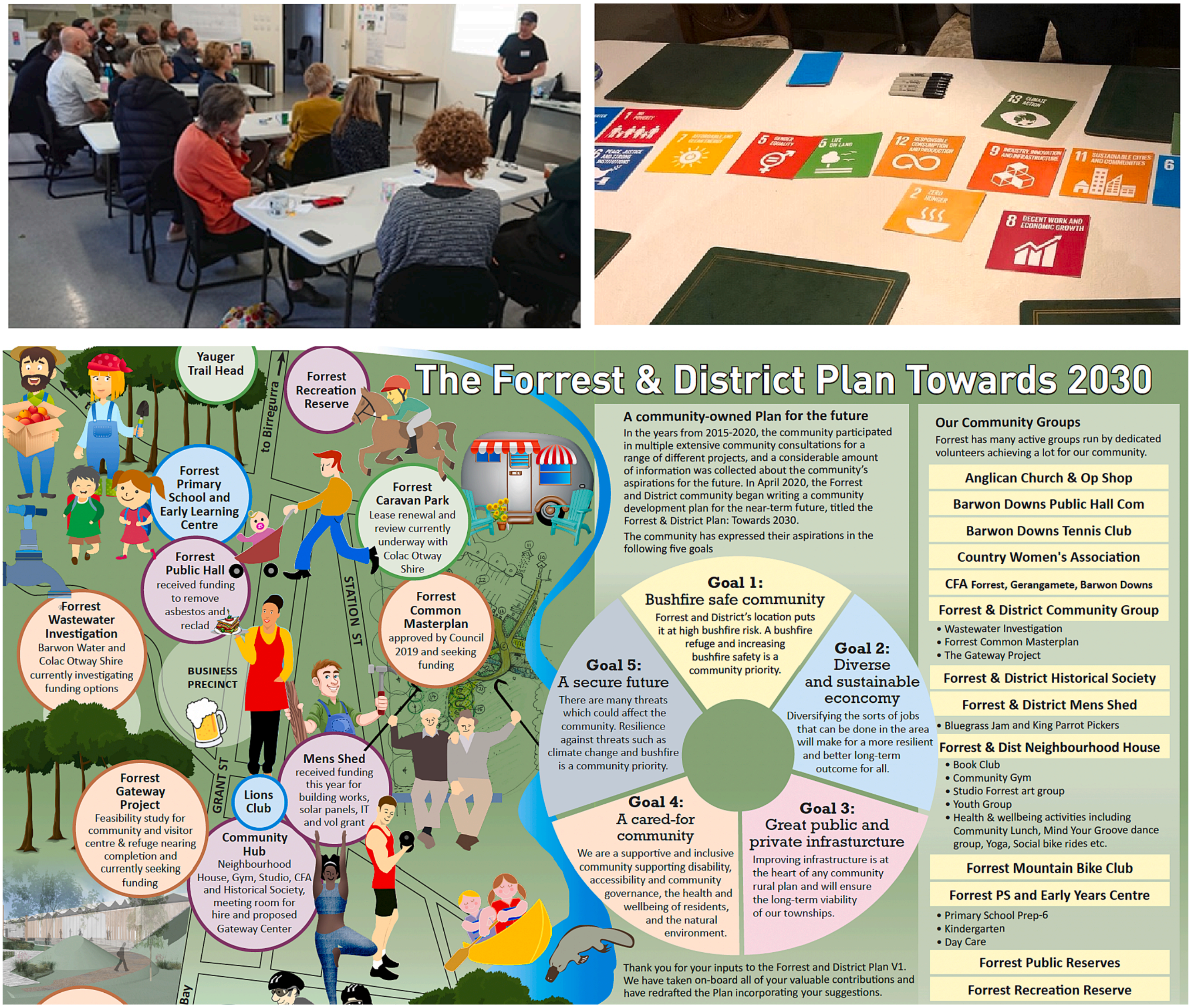

Fig. 8. The local planning process with the community. (Top) Forrest workshops to identify priority SDGs. Photo credit: Enayat A. Moallemi. (Bottom) an overview of the final plan listing priorities, adapted from Szetey et al. (2021b). Infograph credit: the Forrest Post.

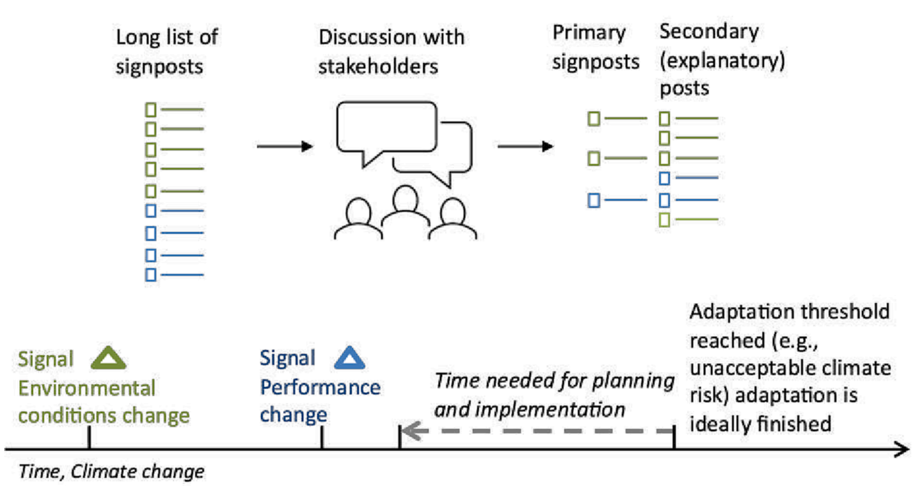

Fig. 9. The participatory process for the design the Delta management monitoring system. Adapted from Haasnoot et al., 2018

Data availability

Access to all data/code is made publickly available through the link and files in the Supplementary Material.

Acknowledgments

We would like to thank the anonymous reviewers for their constructive comments.

Code and Data Availability

Code and supporting data behind this analysis are included in Supporting Materials and at Zenodo: doi: 10.5281/zenodo.7426011.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2023.102727.

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