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 that challenges decisions is rooted in their multi-actor settings, i.e., the poorly understood societal actors with diverse values, complex relationships, and conflicting management approaches. Despite general agreement across disciplines on co-producing knowledge for viable and inclusive outcomes in multi-actor settings, 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 achieved. 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 approaches 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 approaches towards flourishing co-production in supporting decision-making. We find that four general approaches 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; social learning; power relationships; governance inclusivity; and transformative change. Characterising the emergent approaches and their key areas for improvement can help guide future works towards more pluralistic and integrated science and practice.

Keywords

Co-production, stakeholder, sustainability, socio-ecological system, transdisciplinary.

1 Introduction

Nature, people, and policy co-evolve and are inextricably interlinked (*1*), giving increasing importance to an integrated understanding of human-natural systems in recent decades (*2*). A long history of studying human-natural systems has focused on their planning, management, and decision-making under uncertainty (*3-5*) to inform complex challenges, such as the management of global commons (*6, 7*), climate change mitigation (*8, 9*), adaptation (*10, 11*), and sustainable development (*12, 13*), in a changing world.

Within the context of human-natural systems, a major source of uncertainty is related to their multi-actor settings (*14, 15*), i.e., diverse societal actors (including individual citizens, local/Indigenous communities, technical experts, NGOs and advocacy groups, industry/business partners, financial sector/markets, and government/decision-makers (*16, 17*)) involved who create a plurality of human interests, conflicting policy objectives, and behavioural and institutional ambiguity (*18*). 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 policy experience (e.g., decision-maker's conflicting objectives, power relationships) (*19, 20*) through approaches that support interactive arrangements among all (academic and non-academic) actors for defining the issues, researching them, and delivering impacts to the society, commonly known as *co-production* (*21*). Co-production promises to improve decision quality through deliberation and collaborative management in a way that can lead to viable, fair, and inclusive solutions (*22, 23*). It also recognises the role of actors in shaping behaviour and empower their actions as the paramount drivers of systems change (*15*).

To realise the compelling promise of co-production, different endeavours are emerging across disciplines that provide empirical guidance for engaging with societal actors in scientific work (*1, 15, 21, 24-27*). Studies have used different theories and terminologies (e.g., co-creation (*3, 28*), co-design (*29*), co-production (*30*), co-engineering (*31*), governance partnership (*10*), action-oriented knowledge (*32, 33*), transdisciplinary and participatory research (*34*), post-normal science (*35*)) and employed various qualitative and quantitative approaches that combine computational and human capabilities interactively (*24, 36*). These advances have made co-production a cornerstone of managing human-natural systems with its importance being widely recognised in the service of societal and policy change (*3, 30*).

Despite significant work in areas such as sustainable development (*21, 25*), climate change (*37, 38*), conservation (*16*), and ecosystem services (*39*), there is still poor conceptual clarity about co-production in planning, decision-making, and management of human-natural systems in a changing world (hereafter, in short, decision co-production). Past efforts in this area have been limited in focusing on specific sectoral domains (e.g., water (*40*)), individual decision-making processes (e.g., problem formulation (*41*), scenario framing (*42*), risk management (*43*), governance (*44*)), and certain actor interaction modes (e.g., eliciting information (*45*), social learning (*46*), co-designing plans (*47*)). This narrow focus indicates a distinct lack of understanding of the diversity of decision co-production approaches 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 which are diverse in terms of time horizon (i.e., short-, medium-, long-term) and 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) to reflect on a wide range of empirical experience (Figure 1). We characterise their distinct choices, differences, and trade-offs through content analysis and clustering (Section 2) to serve two aims. The first is to synthesise key recurring approaches through which co-production is motivated, designed, and leads to impact in decision-making under uncertainty (Section 3). Characterising these approaches is important to define what best-practice co-production means in decision-making and how 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 co-productive decision practices in the future (Section 4). This can lead to a deeper understanding of the barriers in realising the approaches of effective co-production and provide recommendations to design inclusive decision processes with fair outcomes.

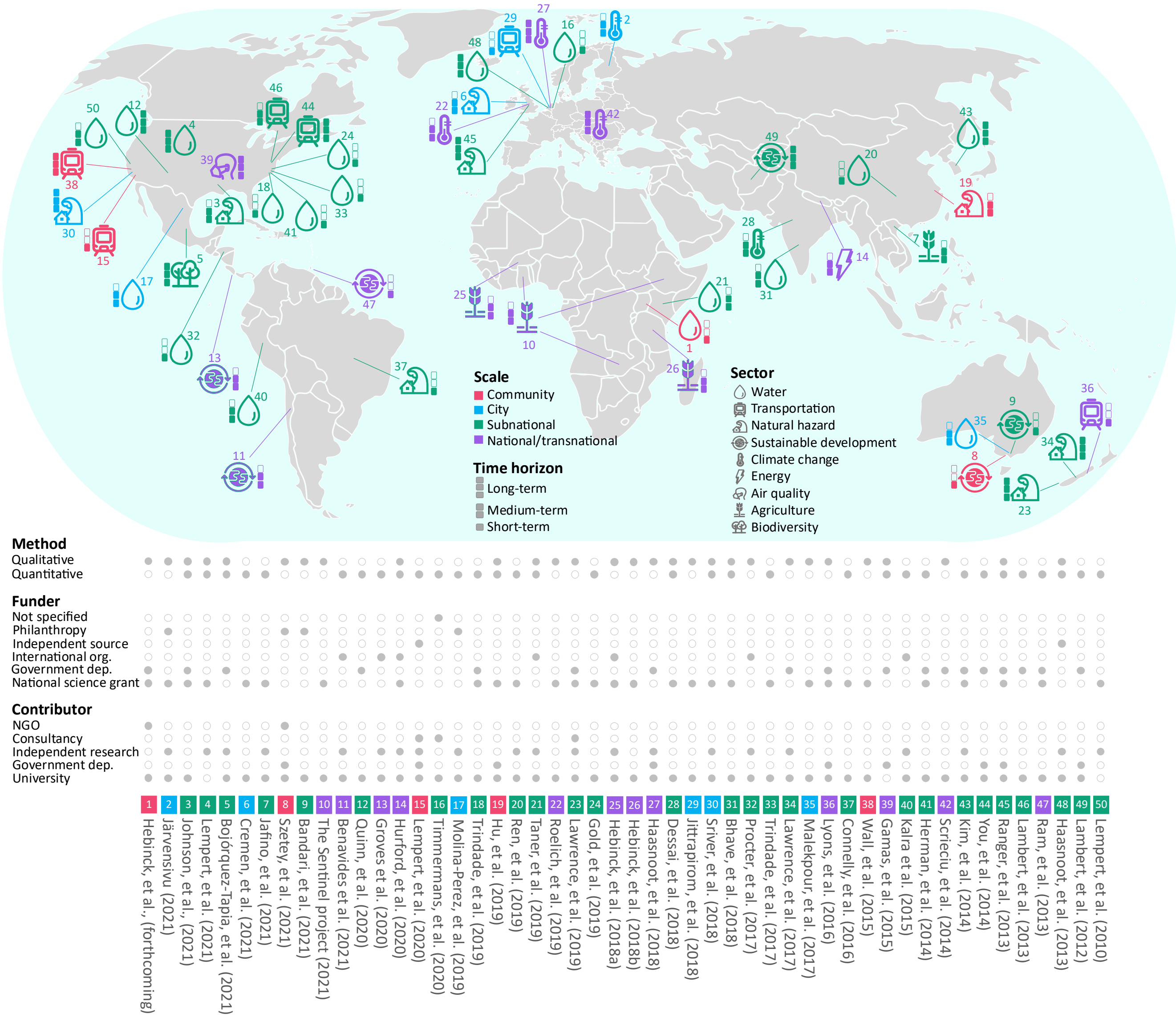

Figure 1. The case studies analysed for decision co-production. Cases are related to decision-making under uncertainty and are selected in the context of human-natural systems. Online access to all cases is available in the case details tab in Supplementary Data 2. Icons for water, transportation, natural 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.

2 Methods

2.1 Case selection

We selected a mix of cases (qualitative, quantitative) of decision-making under uncertainty for an in-depth analysis of co-production approaches. 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 (*48*), 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.

The details of the systematic search (e.g., database, keywords, selection criteria, search results) are explained in Supplementary Text. This systematic search resulted in 246 publications (Supplementary Data 1), 36 of which were identified as relevant based on the selection criteria. 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 (Supplementary Data 2) to be used for content analysis.

2.2 Content analysis

To synthesise the key approaches from the selected cases, we performed *content analysis.* First, we extracted a set of meta-information from the selected cases (the case details tab in Supplementary Data 2), 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). 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 (Figure 2) in relation to motivation for co-production (*Framing, Solving, Acting*), settings for engagement (*Actor, Timing, Interaction*), and impact materialised on the ground (*Power, Politics, Change*).

- **Motivation:** The first three 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 (*49-52*). In line with these previous studies, we broadly categorised the motivation for decision co-production as: *Framing* (a.k.a. decision scoping (*49*), priority setting (*53*), problem formulating (*41*), stage setting (*54*), future framing (*55*)); *Solving* (a.k.a. analysing problem (*24*), evaluating solutions (*56*), assessing scenarios (*57*)); and *Acting* (a.k.a. executing and implementing (*58*), communicating (*47*), monitoring and evaluating (*59*)).
- **Setting:** The next three 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 extract 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* (*17*) to explain which stakeholder groups, at different levels of stake and influence, participated in co-production; *Timing* (*60*) to indicate when (beginning, end) and with what frequency (once or twice, multiple times) they engaged with actors throughout decision-making; and *Interaction* (*61*) to specify the direction of information circulation and exchange of information (one way, two-way, interactive).

- **Impact:** Decision co-production is not only about improving scientific efforts, but also about creating the potential for impacts on the ground. This relates to understanding 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 (*10*). The last three features described the ways in which the impacts from decision co-production are catalysed (*what* to achieve?). We used three conceptualisations of impact (*22, 25*) in terms of: *Power* (*62, 63*) as the actor's ability to create or resist change, exercise power over other actors, and create conflicts and cooperation ; *Politics* (*22, 64*) 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* (*20, 65*) as the extent of achieving a real-world impact on the ground and shaping transformation.

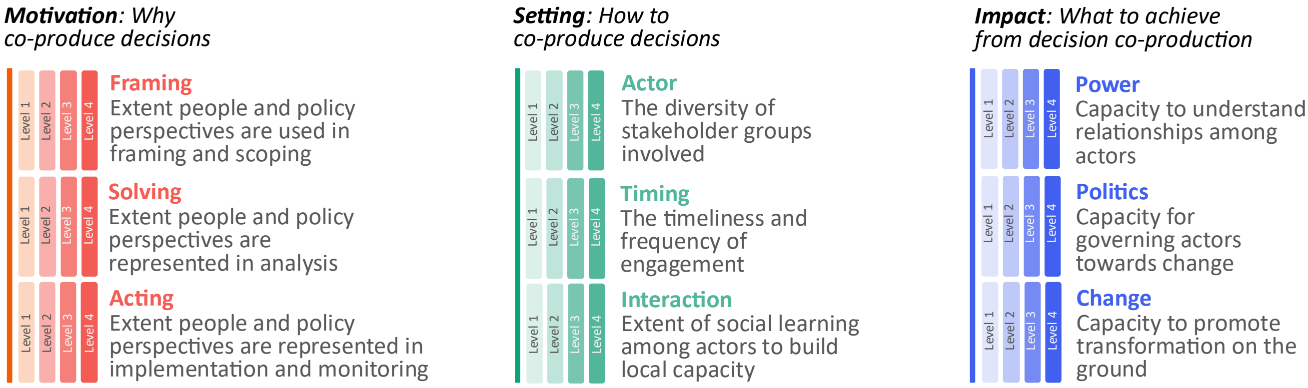

Figure 2. A summary of features used to characterise the decision co-production cases. See Supplementary Text for definitions of each feature and their guiding levels.

These features may not be fully comprehensive in showing all decision co-production qualities, but they cover a range of important ideas in relation to decision co-production that build on previous work on analytical objectives in decision-making (*50, 66*) (related to Motivation), settings of participatory modelling (*60, 67*) (related to Setting), and the role of human agency and societal change (*25, 62*) (related to Impact).

We mapped the quality of co-production in the cases against these nine 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 (Figure 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, we performed *clustering* to group the cases based on their similarity in relation to the nine features. This was to identify the important recurring approaches and emergent themes observed in several cases which transcend the details of individual cases. To cluster the coded cases from content analysis, we used a k-*means* clustering algorithm that is commonly used in quantitative analysis (*68*) on the basis of its performance compared with other algorithms, 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.

$$EV_k = 1 - \sum_{k=1}^{k} SSE_k / SSE_{all}$$ **Equation 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 Figure 1). We specifically looked at the changes in explained variance (Equation 2) which indicates how much an additional cluster would improve the explained variance.

$$\Delta EV_k = EV_k - EV_{k-1}$$ **Equation 2**

Following the process set in a previous study (*68*), 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 identify the optimal number of clusters. This led to four clusters as the optimal number (Supplementary Figure 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 approaches identified through clustering came with strengths and limitations, represented in their different extents of co-production 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 cases. The gaps and the ways to address them indicated areas for future improvement.

3 Charactering key approaches in decision co-production

Despite the uniqueness and diversity of the cases reviewed, our results show that general clusters of approaches for decision co-production emerge from the similarity of the cases across nine features (Figure 3). These clusters indicate four distinct approaches focusing on *Innovation* in developing and adopting qualitative and quantitative methodological advances; *Implementation* in working on the integration of people's world view and policy experience across systems and locations; *Collaboration* in enabling genuine participation; and *Transformation* in facilitating change-making on the ground. These four approaches 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 approaches in isolation would be enough, and collaborative processes in support of decisions should benefit from all four approaches to maximise effective co-production practices. We explore these key approaches and highlight their nuances with reference to cases in the following.

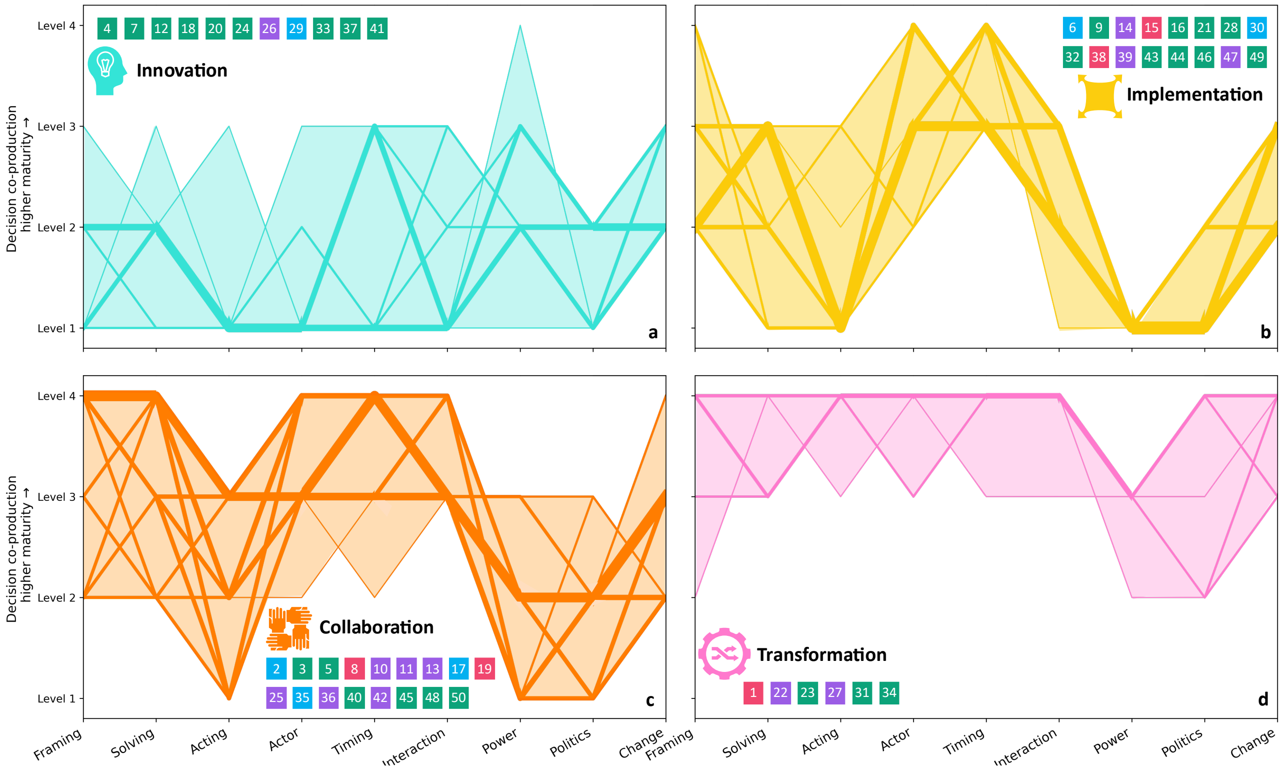

Figure 3. Characterising the cases against the nine features and the resulting four clusters of decision co-production approaches that emerge from the similarity of the cases. The approaches emerged based on the similarity of cases across nine features related to Motivation (i.e., Framing, Solving, Acting), 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 approach are shown in the subplots with boxed numbers that are further detailed in Figure 1. Icons by Nikita Kozin, Kemesh Maharjan, ProSymbols, and Nithinan Tatah from the Noun Project under a Creative Commons License CC BY 3.0.

Innovation. The first approach, seen in 22% of the cases, is focused on the development and testing of innovations in formal methods for more robust and equitable decisions (Figure 4). 82% of the cases that share this approach 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 (*69*), conflict resolution (*56*), equity between actors (*70*)). Most (82%) of these cases are focused on problems related to water and agriculture, but their innovative research approaches are generic enough to provide helpful analytical tools for similar problems in other sectors that operate in a multi-actor setting (e.g., tools to guide long-term infrastructure investment (*71*), identify trade-offs between conflicting objectives (*69*), address tensions between multiple worldviews (*41*)). 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 employ inputs from societal actors for decision framing and analysis (e.g., problems with conflicting policy objectives (*72*), future uncertainties (*73*), and alternative performance metrics (*69*)) rather than engaging with people for acting and implementation (Figure 3a). These cases also often remain limited to eliciting information (rather than facilitating knowledge exchange). This can be in the form of technical expertise from selected elite groups (e.g., researchers, domain experts/practitioners, as defined in Turnhout *et al.* (*22*)) and be used for informing policy change through 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.

The cases that focus on Innovation remain impactful on the ground. They enable the exploration of the complexity of actor relationships with new analytical tools and therefore contribute significantly to the understanding of power dynamics (e.g., identifying winners and losers (*70*), actionable compromises (*56*)). However, most of them discuss the politics of managing these actor relationships and their governance towards change only in limited ways (Figure 3a).

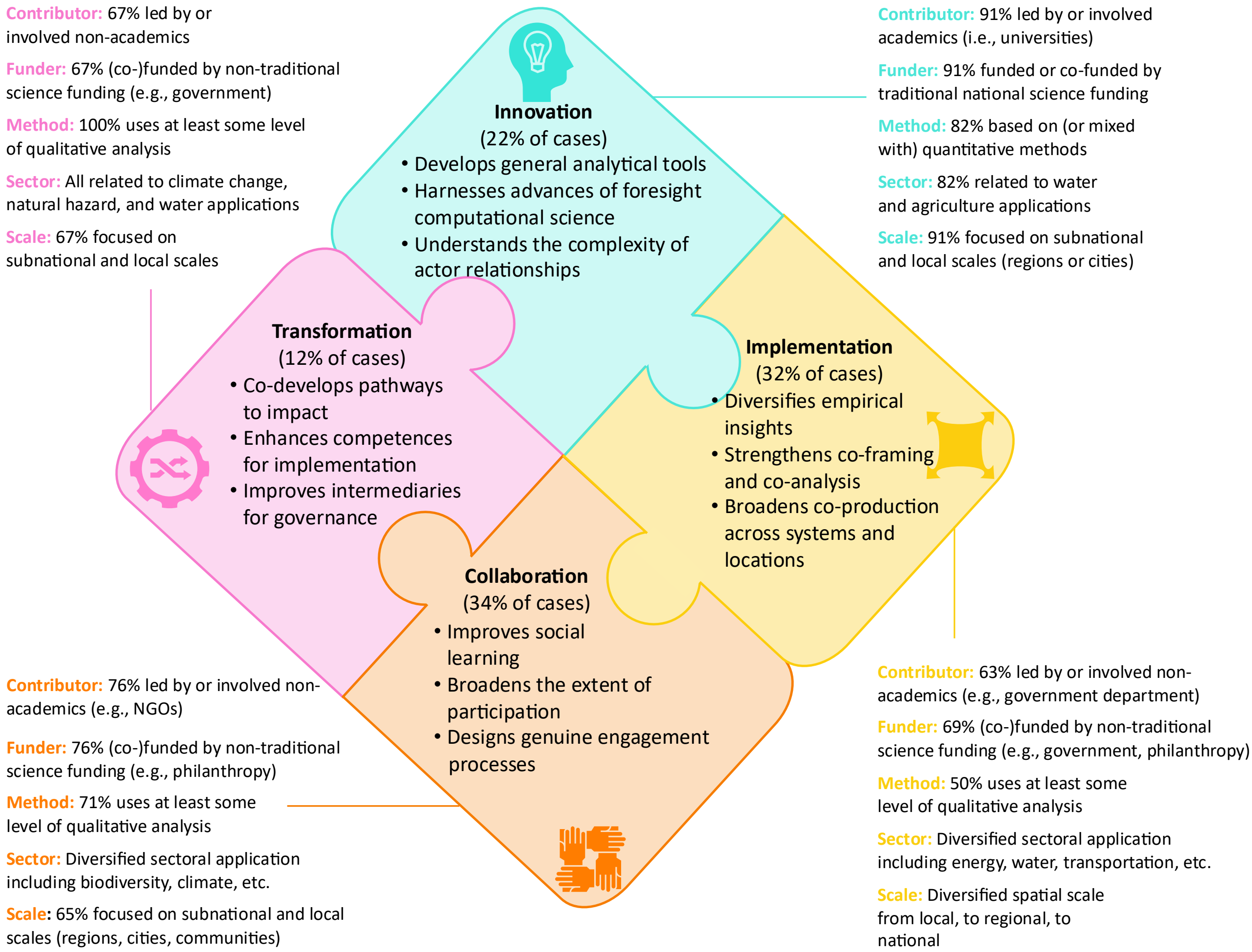

Figure 4. The key area of focus in four approaches for decision co-production. Decision co-production in human-natural systems should be innovative (i.e., innovation-focused), applied across systems (i.e., implementation-focused), collaborative (i.e., collaboration-focused), and guide towards creating change on the ground (i.e., transformation-focused). These four approaches, observed and repeated across 50 cases, together underpin high quality decision co-production.

Implementation. The second approach, 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 (local, national, transnational), and locations (Figure 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 (69% co-funded by beyond national science programs, e.g., via philanthropy, international organisations, and government departments) and their more diverse team of contributors (63% involved organisations beyond universities such as government and independent thinktanks).

Cases featuring Implementation are guided by strong problems framing and analysis (e.g., priority setting (*53*), policy sensitivity analysis (*74*), risk assessment (*45*)) with societal actors (Figure 3b). Actors are usually closely engaged from the early stages (e.g., via project inception and problem-solving workshops (*45*)) to navigate different views and create a space for deliberation among actors. However, these efforts have less of a focus on acting and implementing decisions. Unlike the Innovation approach, co-production in the Implementation cases extends beyond eliciting information and is supported by efforts to understand differences and facilitate the exchange of knowledge (e.g., using visual analysis plots (*74*), the Chatham House rule (*75*), brainstorming (*76*)) with a wider range of societal actors (e.g., expert, decision-makers, citizens in the community).

Despite the significance of the Implementation cases in diversifying and contributing to application, most of them have a limited discussion of impact on the ground (Figure 3b), only theorising or informing policy (e.g., via better understanding system complexity (*53*), performance under uncertainty (*77*)) to influence powerful actors (e.g., investment decision-makers (*78*) and planners and managers (*79*)). There is also typically little or no discussion of the politics and how to enable transformative change through broader empowerment of societal actors (Figure 3b).

Collaboration. The third approach, seen in 34% of the cases, is focused on fostering social learning and inclusive and genuine participation (Figure 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 foster consensus among diverse views. The cases that share this approach 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 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 (i.e., 76% co-funded by non-traditional sources such as philanthropy and NGOs) and a more diverse team of (76% non-academic) contributors.

The Collaboration cases broaden the extent of participation to represent wider actor groups beyond elite actors and include voices that are often marginalised (e.g., citizens, advocacy groups (*80, 81*), local communities (*82*)) (Figure 3c). They also deepen the nature of participation to promote co-learning to ensure actors can learn from each other (*83*), reflect on their perspectives (*84*), and co-design with other actors to improve the ownership of the results (*82*). The diverse and inclusive participation across the Collaboration cases is reflected at all stages from early steps such as framing of the problem through participatory activities to ascertain the shared aspirations and normative views (*82*), to intermediary steps such as the analysis of drivers and barriers for interventions (*84*), and final steps such as validation and modification of findings based on actors' feedback (*80*). 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 approaches (Figure 3c). These cases start to discuss the role of societal actors in implementation settings (e.g., by proposing detailed action plans (*85, 86*)). The cases also bring a more explicit understanding of power relationships among actors (e.g., discussing corrective/empowering interventions for power imbalances (*81, 83*)) and how they might be governed (e.g., influencing powerful actors (*80, 87*), empowering marginalised groups (*88, 89*)). However, while Collaboration cases co-produce knowledge to inform policy for change (e.g., advising governments on plans (*90*)), often they do not discuss how to co-manage transformation on the ground with societal actors (Figure 3c).

Transformation. The fourth approach, seen in 12% of cases, is focused on enhancing competencies for effective implementation and shaping pathways to impact, as the outcomes of the collaboration (Figure 4). The cases that share this approach often design participatory approaches that can potentially integrate people's knowledge and policy experience throughout the key stages of managing human-natural systems. Examples include the joint framing of priorities and options (*91*), interactive problem solving (*92*), and collaborative implementation and monitoring (*59*). Co-production is achieved through sustained and meaningful dialogues with societal actors, including citizens, local/Indigenous communities, and policymakers; and decisions about important issues are made jointly in a knowledge co-production process.

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 (e.g., through gaming (*91*)), so that alternative routes can be designed in response to potential barriers (*93*) (Figure 3d). An improved understanding of power and agency can 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 approaches, Transformation cases can improve governance capacity by distributing responsibilities between actors (*92-94*) and enable change by providing a range of intermediary tools (e.g., pathway development, monitoring, contingency planning (*58, 59*)).

4 Towards flourishing co-production in decision support

Individual approaches in isolation, each with certain limitations and strengths, cannot lead to high-quality decision co-production, and therefore none of the discussed cases represent the "best" or the "ideal" approach. Rather, co-production in decision-making needs to be underpinned by learning from and integrating the most constructive and complementary features of all four approaches. We explain what these approaches can learn from one another by discussing some of their main *challenges* and *opportunities* (Figure 5), drawing on several best-practice examples from global case studies. The purpose of discussing challenges and opportunities here is not to be fully encompassing, but rather to highlight important deficits and exemplify promising ways to improve co-production in decision support.

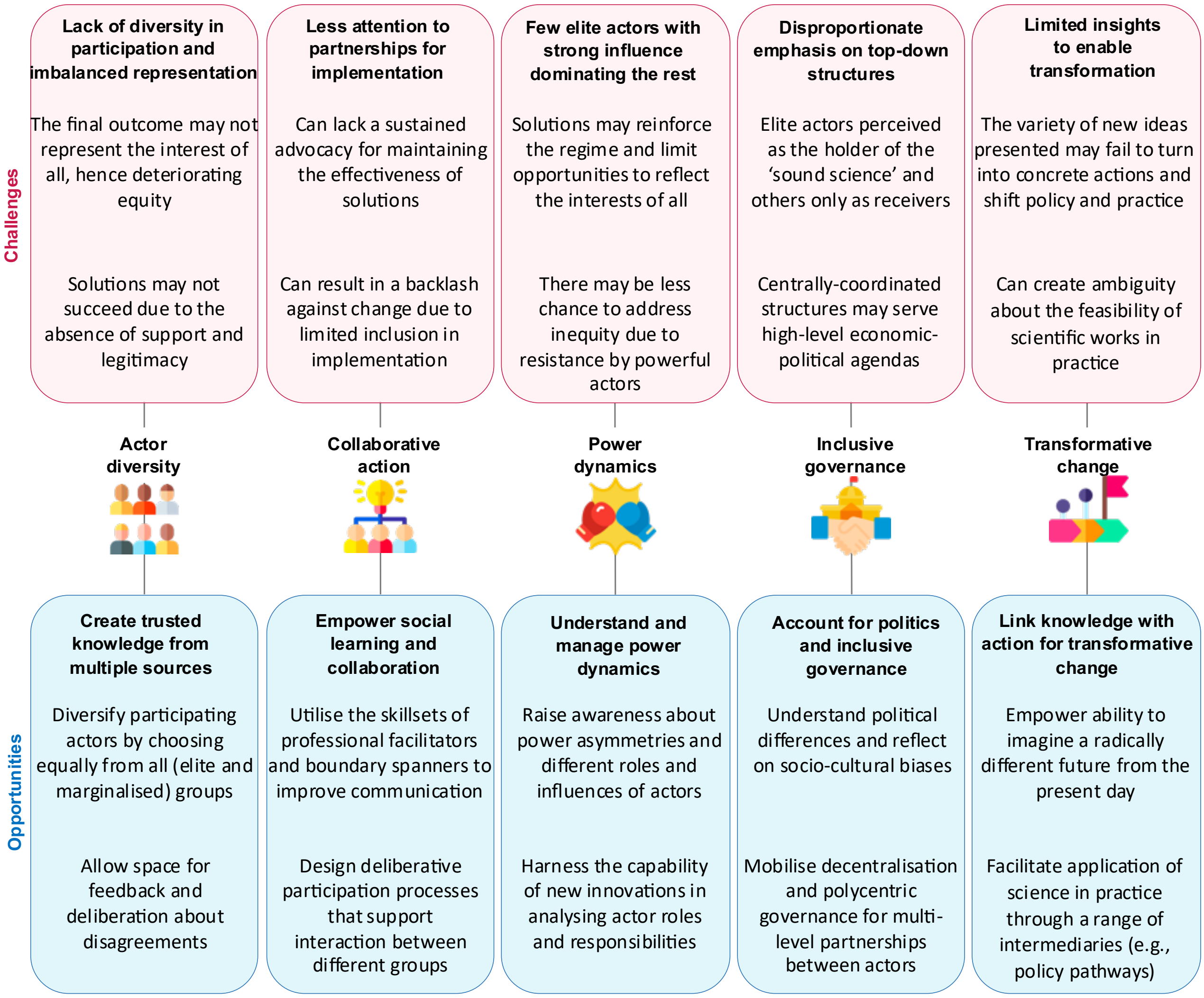

Figure 5. Examples of challenges and opportunities in decision co-production. They are synthesised across the cases and shared among the identified decision co-production approaches (see Methods in subsection 2.4). Icons by Freepik and Smashicons from www.Flaticon.com under free personal and commercial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

Actor diversity. Managing human-natural systems requires approaches beyond technical solutions, and should involve the knowledge of different societal actors (e.g., needs, capacities, cultural values, hidden preferences) to increase the chance of success (*95*). 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 was at Levels 1 or 2 of the Actor axis in Figure 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 diversified actor groups; not only elite actors (e.g., government bodies, technocrats, scientists, large NGOs (*22*)) 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 (*96*)), potentially leading to more legitimate, credible, and relevant outcomes (*16*). This diversification 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 (*25*). 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 (*94*). Tools 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 (*17*).

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 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 (*87*). 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 (*82*). The unwillingness of actors to engage is another risk (*95*), which often requires designing participation (e.g., prioritising when to approach actors throughout the process and for what type of knowledge (*97*)) in a way that minimises engagement fatigue. Here, a 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 (*24, 30*). 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. Another similar experience was in the case of robust planning for urban water management in Monterrey, Mexico (*86*) 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).

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 (*86*). 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 (Figure

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 (Figure 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.

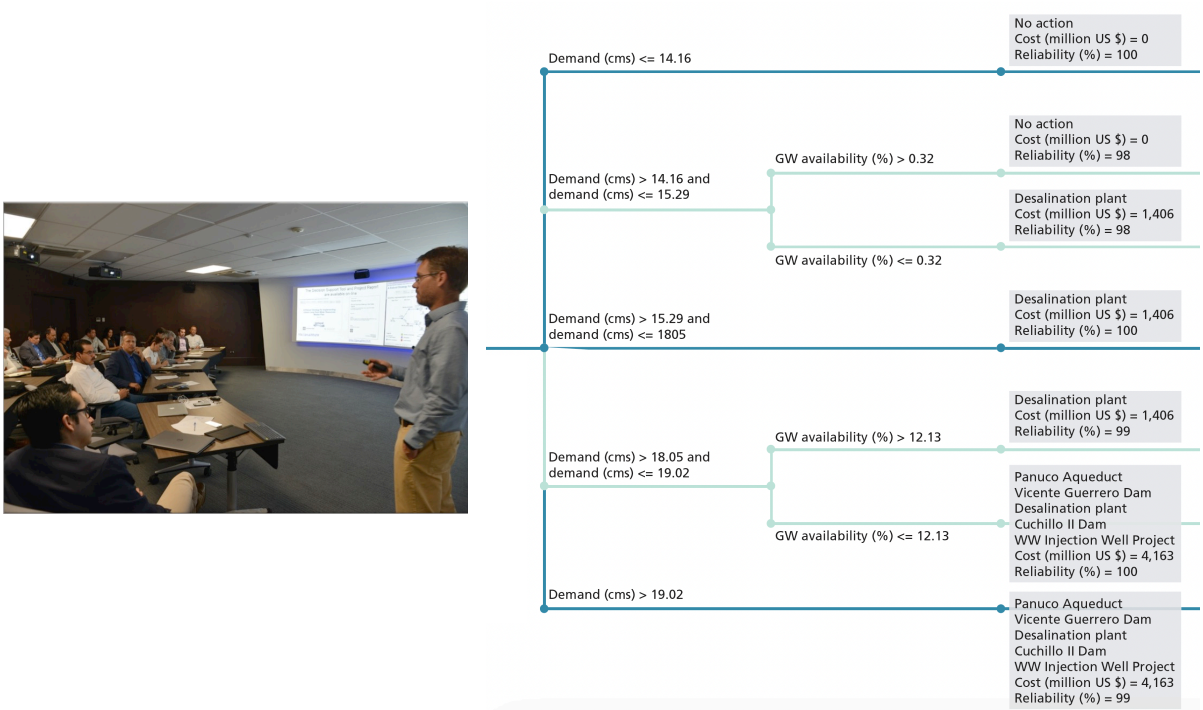

Figure 6. Participatory urban water robust decision-making. (Left) the decision framing workshop to identify vulnerability conditions, photo credit: Tecnológico de Monterrey. (Right) a simplified version of the decision co-production output, i.e., the adaptive water strategy, see the full version from (*86*), figure credit: RAND Corporation.

Collaborative action. Understanding the plurality of perspectives that different actors provide needs to be accompanied by social learning between them (e.g., for raising awareness, changing people's perspectives) to enable broader societal impact (*98*). It should also lead to collaborative decision-making, not only in establishing priorities or analysing solutions together, but also supporting *action* on the ground with actors 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 (*62*). Despite this, most cases describe little or no collaboration among actors in acting on decisions (e.g., 91% and 88% of Innovation and Implementation cases respectively were at Levels 1 or 2 of the Acting axis in Figures 3a and 3b). This is an important gap for maintaining the long-term effectiveness of decisions as actors support them if they can see the relevance in terms of social identities and cultural traditions (*98*). The limited inclusion of actors in the implementation of decisions may also promote scepticism and damage the sense of ownership, resulting in a backlash against change (*99*).

The first step is to create the capacity for collaborative action. One way to do this is through improving communications with a common language (whether that be eliminating jargon, or using different languages) that span the boundary between different groups, as discussed theoretically (*29, 100*) and also experienced in practice (e.g., in workshop design for carbon neutrality planning in Chile (*90*)). 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 (*101*), commonly referred to as boundary spanners (*26*) or knowledge brokers (*102*). 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 (*10, 103*) to bridge the distance between the research team and the community and create trust and a sense of ownership of the outputs. Examples are the two cases of local, community-driven sustainability planning in southern Australia (*47, 53*) where collaboration with professional facilitators and workshop consultants resulted in higher willingness for participation among the local communities and more effective outcomes for the research team.

There are a range of other participatory tools that can offer different levels of analytical capability and build the capacity to co-produce decisions (*61*). 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 (*104*). A related case is that of regional climate adaption planning in Karnataka, southern India (*75*) 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 on the ground. 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 (*105*), which have built up expectations and co-produced insights on major challenges and pathways to the future in a collaborative manner (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 (*41*), experimenting with solutions (*57*), or finding relevant compromises when human perspectives are in conflict (*56*).

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 (*81, 83, 89*).

The 3-day workshops took place in or close to the capitals of Ghana, Ethiopia, and Zambia (Figure 7). Around 25-30 local stakeholders from policy, the private sector, NGOs, and academia participated in the workshops, which were facilitated and hosted by 3-4 researchers from the local university and 3-4 project-researchers from the UK. Most participants did not have any previous experience with foresight or scenario development. The participation of a diverse set of actors, with diverse experiences and knowledges about agricultural development, was vital for identification of scenarios which were sophisticated and complexity in terms of scales and system relations.

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.

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

Power dynamics. Understanding power and agency and ensuring reciprocity underpin efforts to manage conflicts and cooperation between actors and can enable redistribution of access to resources (e.g., infrastructures, technologies), which is necessary to shifting power imbalance and inequity (*62*). However, power and agency are not yet sufficiently addressed in support of decision-making where most cases have little or no understanding of power (e.g., 100% and 82% of Implementation and Collaboration cases respectively were at Levels 1 or 2 of the Power axis in Figures 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 inequalities among those highly affected by the imposition of outcomes but who are relatively powerless in policy decisions (*30*).

Confronting asymmetries and providing opportunities to those with a lived experience of inequality (e.g., underserved regions, Indigenous communities) to take part is important (*106*) to shift the discourse from ‘power over’ (some actors are dominated by others) to ‘power with’ (all actors are empowered and contribute) (*62*). 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 (*80*). Diversified funding sources and contributors can provide new motivation to focus much more keenly on social elements and engage with underrepresented groups (*107*). 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 (*22*).

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 (*93*). Complex contexts, with conflicting priorities and solutions that affect various actor groups in different ways, may also require methods of higher analytical capability. Recent methodological advances in data analytics have emerged to map complex power relationships (*63*), evaluate equity between actors (*108*), and explain potential cooperation and conflicts, which have not been fully exploited in practice. For example, in North Carolina in the US (*56*), 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. 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 (*109*). Combining these advances in future co-production projects can offer opportunities for addressing some of the current challenges.

Inclusive governance. Politics as the act of deciding who does what, when, and how (*110*) is a key factor in connecting science with policy and action to effect change. However, the inherently politicised nature of science-society relationships is largely undiscussed among the analysed cases (e.g., 100% of Innovation and Implementation cases were at Levels 1 or 2 of the Politics axis in Figures 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 (*30, 111*). 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 (*22, 112*).

Different ways have been suggested to improve the focus on politics and enhance the democratic quality of working with societal actors (*113*). For example, some studies (*114, 115*) 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. Careful design of co-production processes to fit the context is of critical importance to navigating the boundary between politics and science *(29).* 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 (*112, 116, 117*).

Another example from STS is Jasanoff (*118*) 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 (*119, 120*), is also commonly seen in our case studies to be top-down. 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 (*121*).

Suggestions have been made for working towards more inclusive governance with stronger emphasis on actors at the local scale and 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 (*119, 122, 123*). 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 (*124*). 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 (*47*). An example of this is a case of local planning in a small community in southern Australia (*47, 82*) which adopted a local lens and used the SDGs as a framework to enable bottom-up governance (Box 3).

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.* (*47*) 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 (Figure 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. (Figure 8).

The synthesis of the community's sustainability goals 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.

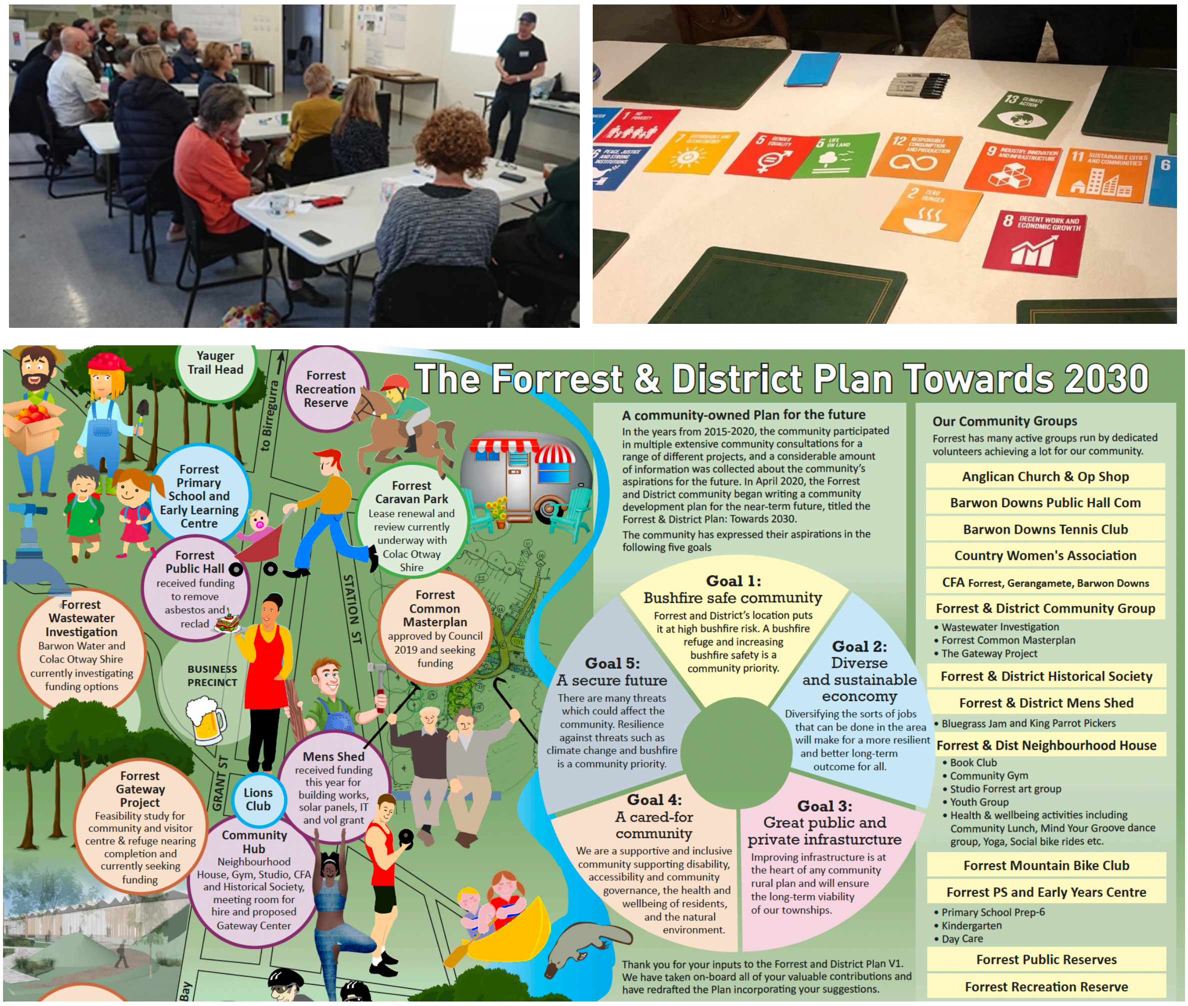

Figure 8. The local planning process with the community. (Top) Forrest workshops to identify priority SDGs, photo credit: Enayat A Moallemi. (Bottom) an overview of the final plan listing priorities, adapted from (*47*), infograph credit: the Forrest Post.

Transformative change. It is broadly acknowledged that catalysing societal and policy transformation is a crucial component in managing human-natural systems (*125*), yet most of the cases focus on scientific recommendations and do not specifically discuss change in terms of understanding barriers to reform and deficits in the capacity to transform (e.g., 73% and 56% of Innovation and Implementation cases respectively were at Levels 1 and 2 of the Change axis in Figures 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 (*32*). Alternative ways have been offered to improve this link. One is through empowering transformative capacity among people and policymakers, i.e., their ability to imagine a radically different future from the present day, and co-design pathways to achieve this future using different types of participatory activities that employ some form of visioning or scenario development (*126*). There is no single 'right' way to the future, and there are multiple alternative pathways (*20*) rooted in the context of each problem. The diversity of local conditions can lead to numerous opportunities in the pursuit of change (*24, 106*). By engaging with societal actors, pathways become inclusive processes that use human knowledge to inform change towards imaginative and anticipatory futures (*44, 55*). 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 (*127, 128*). Hence, these studies highlight that the process of integrating actors should become part of the broader political agenda to shift this dominant view (*22*). This conclusion is shared by other contributions to the literature which synthesise aspects of co-production (*30, 129, 130*) and could be said to be the principal motivation for the use of knowledge co-production in science to support decision-making.

There are also other approaches that can facilitate the translation of knowledge in action. Among them is the idea of *policy pathways* (*58*). 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 (*63, 131-133*) 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. 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 thresholds to trigger the next phase of agreed solutions). One example is the co-design of a monitoring system in the Netherlands' Delta Program (*59*) to support the implementation of planned interventions against flooding in a way that can improve adaptation decisions on the ground (Box 4). There is also a growing number of other research case studies and theoretical frameworks being developed to design policy pathways (*131*). 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 (*134, 135*).

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 (*59, 136, 137*).

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 (Figure 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. 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 outcome included primary signposts that were required ('need to know') and secondary (explanatory) signposts that could assist analysts to better understand the information obtained ('nice to know'). The discussion with stakeholders continued until a balance between having sufficient lists primary and secondary signposts was reached. This means that the initial design of the monitoring system was being adjusted as greater insight was gained on the potential performance of the signposts, their signal values, and their importance for adaptive planning. This was important to allow for new signals that were not part of the standard signposts (e.g., a pandemic, new societal preferences).

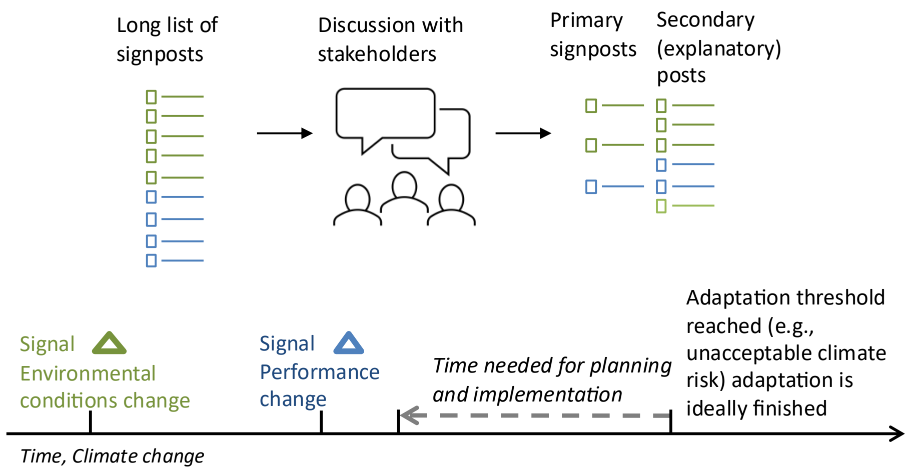

Figure 9. The participatory process for the design the Delta management monitoring system. Adapted from (*59*).

5 Conclusion

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 (*138, 139*). 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 approaches for co-producing decisions with people and policymakers. While these identified approaches 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.

By exploring cases that had different approaches, challenges, and opportunities, we conclude that the question we face is not about what group of cases or which approach is better than others. We argue that integrating the constructive features of all different approaches 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 (*24*).

Acknowledgments

Supplementary Materials

The Supplementary Material file includes:

- Supplementary Text
- Supplementary Figure 1
- Supplementary Data 1
- Supplementary Data 2
- Supplementary Data 3

Code and Data Availability

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

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