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# 1 Six modes of co-production for the sustainable development of ecosystems

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52 **Abstract**

53

54 The promise of co-production to address complex sustainability challenges is compelling. Yet, co-  
55 production – the collaborative weaving of research and practice – encompasses diverse aims,  
56 terminologies and practices, with poor clarity over their implications. To explore this diversity, we  
57 systematically mapped differences in how 32 initiatives from six continents co-produce diverse  
58 outcomes for [the sustainable development of ecosystems](#) at local to global scales. We found variation  
59 in their purpose for utilising co-production, understanding of power, approach to politics, and  
60 pathways to impact. A cluster analysis identified six modes of co-production: (1) researching  
61 solutions; (2) empowering voices; (3) brokering power; (4) reframing power; (5) navigating  
62 differences; (6) reframing agency. No mode is ideal – each holds unique potential to achieve  
63 particular outcomes, but also poses unique challenges and risks. Our analysis provides a heuristic tool  
64 for researchers and societal actors to critically explore this diversity and effectively navigate trade-  
65 offs when co-producing [sustainability](#).

66

67 **Introduction**

68

69 Co-production is a rapidly growing endeavour, [now widely applied in the fields of health,](#)  
70 [development, education, climate change, industrial production, and sustainability](#)<sup>1,3-5,2,6</sup>. It broadly  
71 seeks to connect researchers with diverse societal actors to collaboratively and iteratively produce  
72 knowledge, action and [societal change](#)<sup>1</sup>. The promise is compelling: developing solutions through  
73 legitimate processes that draw on diverse and credible expertise with, by, and for those best placed to  
74 use them<sup>5,7,8</sup>. [Sustainability is one important arena in which co-production has been increasingly](#)  
75 [practiced and examined](#)<sup>1,5,9</sup>. Yet, both the meaning and outcomes of co-production remain ambiguous,  
76 as efforts now employ diverse terminologies – for example, collaborative governance<sup>10</sup>, social  
77 learning<sup>4,11</sup>, co-design<sup>12</sup>, transdisciplinarity<sup>13-15</sup>, and participatory action research<sup>13</sup> – linked to varied  
78 approaches with different goals, theories, practices, [capacities](#), and outcomes<sup>1,4,13,16-20</sup>. Poor  
79 conceptual clarity of distinct approaches and the lack of systematic empirical analysis of their  
80 outcomes risks framing co-production as a panacea<sup>1,7,9</sup>. Amidst growing concerns over how co-  
81 production efforts may in some cases entrench social inequalities and power relations<sup>7,17,21,22</sup>, or fail to  
82 achieve sustainability goals<sup>1,13,15,23,24</sup>, scholarship points to the importance of exploring multiple  
83 impact pathways, trade-offs among approaches, and cross-scalar dynamics<sup>13,23,25</sup>. Yet, much empirical  
84 guidance to date has been limited by scope, often including relatively few case studies<sup>15,18,26</sup>,  
85 geographical contexts<sup>25,27</sup>, or methodological approaches<sup>28,29</sup>.

86

87 The empirically-based analysis presented here of selected examples of co-production provides a  
88 heuristic tool for researchers and societal actors to understand the growing diversity of approaches  
89 and effectively navigate associated trade-offs when designing co-production [processes](#). Our selected  
90 examples focus on one domain of co-production scholarship and practice [in sustainability – reshaping](#)  
91 [how ecosystems can be managed for sustainability](#). To explore diverse co-production approaches in  
92 this domain, we analysed 32 cases that [sought to advance sustainable development by co-producing](#)  
93 [sustainable interactions between people and terrestrial or marine ecosystems](#) (hereafter, ‘[sustainable](#)  
94 [development of ecosystems](#)’, or in short ‘[sustainability](#)’). We conducted qualitative and quantitative  
95 analyses to identify distinct choices in the design and implementation of co-production cases and

96 connect these choices to potential outcomes, challenges, and risks. We employed an information-  
97 oriented, maximum variation approach to sampling<sup>30</sup>, with 32 cases selected to maximise diversity  
98 for: sectoral involvement, researcher roles, co-production practices, and geographical/scalar locations.  
99 These cases span six continents and operate across local, regional, national, transnational, and global  
100 scales (Fig. 1). They interweave knowledge and action through diverse methods that combine both  
101 descriptive and normative aspects of co-production<sup>1,4</sup>; for example, research-informed co-  
102 management processes<sup>31–33</sup>, (trans)national learning networks<sup>34,35</sup>, and global dialogues<sup>36,37</sup>. All cases  
103 sought to beneficially influence how ecosystems function towards sustainability; yet, aspirations  
104 ranged from more modest goals of mainstreaming knowledge within established policies, to intentions  
105 to fundamentally reshape narratives, practices, policies, and institutions.

106  
107 Our analysis emerged from a desire to examine the choices we knowingly or unknowingly make  
108 when studying and participating in co-production efforts for [the sustainable development of](#)  
109 [ecosystems](#) – both in the aims that are set, and the design choices and practices that shape resulting  
110 outcomes. The iterative analyses identified six modes of co-production defined by how they frame the  
111 *purpose* of co-production, conceptualise *power*, approach *politics*, and theorise impact *pathways*.  
112 Below we describe the diversity of cases, and then explore these four themes. We then introduce the  
113 six modes of co-production and their unique potential to produce particular outcomes and risks,  
114 thereby elucidating when and how particular co-production approaches may be effective and  
115 constructive. We conclude by highlighting some critical trade-offs that arise between different modes  
116 of co-production, and some common features that enhance likelihood of achieving outcomes. We  
117 encourage the use of our analysis, particularly as distilled in our graphical visualisations, as a useful  
118 heuristic tool to guide researchers and societal actors towards more reflexive co-production design  
119 and practice in pursuit of sustainability. The analysis and heuristic presented here are not intended to  
120 [serve as](#) a generalisable checklist of ‘how to co-produce’; rather, our approach seeks to cultivate  
121 flexibility and reflexivity that enable researchers and practitioners to plan as well as improvise what  
122 action is required in their situation.

### 123 124 **Diversity of co-production cases**

125  
126 The 32 cases engaged with diverse sustainability issues related to habitat degradation, climate change,  
127 wildfire, and supply chains. All cases were implemented by and/or extensively researched by the 42  
128 co-authors of this paper (case selection process detailed in Methods). Some cases worked either at  
129 local or global scales, but the majority spanned multiple scales in locations around the world (Fig. 1).  
130 All cases fostered collaboration across at least three sectors, with research, government, NGO and  
131 community actors involved in [most](#) cases. [Societal actors ranged from business CEOs<sup>36</sup> and urban](#)  
132 [planners<sup>38,39</sup>, to indigenous leaders<sup>40,37</sup> and artists<sup>32</sup>](#). The cases employed diverse approaches to co-  
133 producing knowledge and action, such as participatory modelling to inform resource management<sup>33,41</sup>;  
134 research-informed co-management institutions<sup>31,38,42,43</sup>; learning networks or think tanks to guide  
135 practice<sup>34,37</sup>; and ‘labs’ to collectively rethink problems<sup>39,44</sup>. Half the cases engaged people with  
136 similar values and goals, while the other half navigated conflicting agendas, and in some cases, bitter  
137 disputes.

139 The combined budget of the cases reached 120 million (median 500,000) USD, ranging from short  
140 18-month projects to ongoing initiatives of 20+ years (Fig. 1). Leadership teams were typically  
141 dominated by citizens of project localities, except when working in less developed countries. In  
142 addition, two-thirds of all cases were led by at least 50% women. In some cases, research played a  
143 minor role; however, in two-thirds of cases, researchers held relatively greater power over decisions.  
144 The majority of cases spanned at least four disciplines such as ecology, social science, art, and  
145 engineering. Some applied more ‘realist’ research methods (i.e. methods used to describe reality, such  
146 as hydrological modelling), while others emphasised ‘relativist’ methods (i.e. methods that study  
147 ‘reality’ as, in part, socially constructed, like discourse analysis)<sup>45</sup>.

148

149

----- INSERT FIGURE 1 NEAR HERE -----

150

### 151 **Key differences across co-production cases**

152

153 We conducted iterative qualitative analyses to identify key differences in how cases frame and  
154 practice co-production, and pursue **and** achieve distinct outcomes. The analyses spanned 2017 – 2019  
155 and entailed multiple steps (see Methods for details): a) **collaboratively producing** a common inquiry  
156 framework based on exploratory workshops of co-production cases and literature review; b)  
157 systematically selecting diverse cases; c) applying the inquiry framework to gather data on each case  
158 study in collaboration with a case expert; d) conducting a preliminary analysis to identify dimensions  
159 of difference across cases, and then testing and refining **a list of 72** dimensions in two participatory  
160 workshops; e) systematically assigning numerical scores and qualitative justifications for each  
161 dimension of difference for the 32 cases; f) conducting statistical and qualitative analyses to identify  
162 and understand patterns. Four key themes emerged from the analyses; cases varied in their (1) purpose  
163 for utilising co-production, (2) understanding of power, (3) approach to politics, and (4) intended  
164 impact pathways. For each theme (below), cases typically followed one of two approaches, **which can**  
165 **be viewed as opposite ends of a spectrum that sit in tension** (Fig. 2). However, some cases  
166 demonstrated that these tensions are not inevitable and may be spanned in productive ways.

167

168

----- INSERT FIGURE 2 NEAR HERE -----

169

#### 170 ***Purpose***

171 **Why do actors co-produce?** The motivations driving co-production efforts heavily shape them<sup>18,19,46</sup>.

172 We identified two main motivations underlying co-production: to more effectively solve predefined  
173 problems and to **reframe** problems. Examples of **solving predefined problems** include initiatives to fill  
174 knowledge gaps, such as land use impacts on ecosystem services<sup>41</sup>, or collectively manage problems,  
175 such as river pollution<sup>38</sup>. **Examples of reframing problems include shifting people’s focus on ensuring**  
176 **sustainable production of a commodity, to becoming an active steward of the ecosystem on which that**  
177 **product depends – whether farmers/fishers in a local resource context<sup>44,33,31</sup> or corporate actors with**  
178 **global influence<sup>36</sup>**. Earlier problem definition facilitated quicker solutions, but also inhibited  
179 participants from questioning their assumptions. For example, partnerships between researchers and  
180 policymakers **explored more topics** over time, but rarely questioned **their** assumption that a lack of  
181 knowledge was the primary barrier to change. Cases seeking to **reframe** problems engaged actors with  
182 divergent views to either negotiate compromise, or facilitate reframing. Reframing was sometimes

183 pursued unidirectionally (i.e. using knowledge to convince actors), but others created spaces to  
184 collectively question multiple perspectives in ways that placed them on equal ground. Projects that  
185 emphasised reframing often struggled to engage solutions-oriented actors and produce concrete  
186 actions. Cases were therefore often challenged by an *apparent* paradox: they needed to stabilise  
187 problem framings to align actors and empower action, while also questioning problem framings to  
188 spark more diverse and innovative possibilities.

189

## 190 **Power**

191 **How is human agency conceptualised?** Power and agency are inherent to sustainability scholarship,  
192 yet these concepts are interpreted in diverse ways<sup>47–49</sup>. We identified two predominant approaches to  
193 understanding human agency: focusing on the behaviour of actors directly linked to sustainability  
194 problems (e.g. [encouraging resource users to extract less or recuperate habitats](#)<sup>41,50</sup>), versus targeting  
195 more systemic aspects (e.g. addressing [broader paradigms and systems](#) that influence [resource users'](#)  
196 [agency](#)<sup>37,51</sup>). This echoes different definitions of 'power' in the literature, ranging from more direct  
197 interactional forms (i.e. exercising 'power over' others), to diffuse, structural, and preconstituted  
198 forms<sup>47</sup>. While the direct approach was typically seen in cases focused on solving problems, the more  
199 systemic approach often emerged from processes that used iterative dialogue and creative methods to  
200 reframe participants' perceptions of agency<sup>32,44</sup>. Some cases realised contradictions over time between  
201 their direct actions (e.g. supporting local communities to adapt to climate change) and failure to  
202 address systemic issues that constrained those actions (e.g. policies and actors causing climate  
203 change)<sup>40</sup>. Projects therefore struggled to navigate tensions between promoting a limited view of  
204 agency to empower direct action, and expanding views to consider systemic issues that could leverage  
205 wider impact. While the former risked [failing](#) to address the roots of sustainability problems, the latter  
206 risked disempowering individual agency if people felt overwhelmed by 'big' systemic challenges.

207

## 208 **Politics**

209 **How are power relations changed?** Co-production literature increasingly explores the politics  
210 inherent to reshaping relations of power among actors<sup>16,21,52</sup>. [Here we refer to politics as the work of](#)  
211 [deciding who gets what, when and how, which refers to a broader sphere of engagement than the](#)  
212 [deliberation of official government processes](#)<sup>53</sup>. We identified two distinct ways that cases [engage](#)  
213 [with politics to reshape](#) power relations: by empowering marginalised actors, [such as grassroots](#)  
214 [groups or local officials](#), or by influencing powerful actors, [such as international policy makers or](#)  
215 [corporate executives](#), to yield power. Most cases focused on local actors; [for example, by empowering](#)  
216 [municipal officials through provision of science-based evidence to engage political decision-makers](#)<sup>54</sup>.  
217 Some sought to persuade actors to change behaviours defined as problematic by actors external to the  
218 context (e.g. exploitation of natural resources [by farmers](#)<sup>50</sup>), while others began with local  
219 interpretations of problems<sup>43</sup>. Several cases facilitated integration of local and external views to  
220 develop new possibilities for action. Some took the further step of representing these views in  
221 decision-making arenas, or gave local actors a seat in discussions with more powerful actors. Yet,  
222 very few cases [sought to reshape power relations through deep engagement](#) with globally powerful  
223 actors, or directly connected them to iterative bottom-up processes. Indeed, cases that directly  
224 engaged powerful actors rarely questioned their control over particular actors. This dynamic played  
225 out within some project teams, where actors from the global North held greater control over co-  
226 production processes occurring in the global South, with no cases of the reverse<sup>55</sup>. Cases therefore

227 tended either to **not actively attempt to influence the politics that shaped** power relations, or struggled  
228 to **navigate the politics** of shifting power by iteratively engaging one, or occasionally both sides of  
229 power differentials.

230

### 231 *Pathways*

232 **How are impacts catalysed?** Co-production initiatives exhibit diverse possible impact pathways<sup>23,56</sup>.  
233 Our cases employed two main pathways: by primarily producing scientific knowledge as a product  
234 that is expected to shape policy and/or practice (i.e. ‘by producing knowledge’; Fig. 2), or through  
235 more integrated forms of knowing, relating and doing (i.e. ‘by relating together’). **Examples of**  
236 **producing knowledge included developing new scientific research outputs like academic journal**  
237 **articles, or reports for policy-making and practice (e.g. guidelines for practitioners)<sup>54,57</sup>. Examples of**  
238 **relating together emphasised iterative dialogue to share practical experiences of actors**  
239 **involved<sup>36,37,39,44</sup>, and direct action through co-managing ecosystems and creating new institutions and**  
240 **policies<sup>31,32,34,38</sup>. Many cases focused on producing knowledge**, clearly linked to the dominant role of  
241 researchers in our sample of cases. These cases often **quickly** stabilised notions of problems, such as  
242 the need to fill particular knowledge gaps related to interventions, resource/information flows, or  
243 actors’ perceptions. The actors that this knowledge sought to influence were involved in varied ways,  
244 from informing questions, to co-producing research, or engaging in social learning around the  
245 produced knowledge. In contrast, cases that focused less on producing scientific knowledge **outputs**  
246 typically emphasised **relating together**. This latter approach was associated with fewer predefined  
247 goals and more space to enact emergent ideas.

248

### 249 **Modes of co-production**

250

251 The hierarchical clustering<sup>58</sup> analysis grouped cases that similarly approached purpose, power,  
252 politics, and pathways into six clusters (Fig. 3). Clusters represent distinct modes of co-production  
253 that employed particular designs and practices to pursue up to 14 types of identified outcomes. These  
254 **modes** varied in their aims (Fig. 4); for example, some particularly sought to produce scientific  
255 knowledge outputs (1, 2, & 4), reframe pre-existing beliefs and values (2-6), enhance policy uptake  
256 (1, 2, 4, 5), or build institutions (3 & 5). For each **mode**, we discuss their main features and key  
257 strengths and weaknesses in relation to the extent that cases pursued and achieved particular outcomes  
258 (Fig. 4). We connect this discussion to the unique opportunities and critical risks associated with  
259 different approaches to navigating purpose, power, politics, and pathways (Fig. 5).

260

261 ----- INSERT FIGURE 3 NEAR HERE -----

262

263 ----- INSERT FIGURE 4 NEAR HERE -----

264

### 265 *Mode 1*

266 **Researching solutions.** Here, scientists and decision-makers employing more ‘realist’ investigative  
267 methods<sup>45</sup> like ecosystem modelling, produced practical scientific knowledge, **with the goal** to  
268 **influence** policies and interventions. Cases varied in the relative power of scientists or decision-  
269 makers to define topics, but spanned relatively low social diversity of actors. These projects generated  
270 evidence that could inform or justify the approach of environmentally motivated decision-makers.

271 This was most effective within institutional contexts that supported actors to iteratively evolve  
272 relationships, questions, and methods over time, and adapt to shifting policy contexts<sup>54</sup>. However, this  
273 approach was less effective at shifting the strategies and priorities of decision-makers, who were more  
274 receptive to knowledge that helped rather than opposed their plans. The emphasis of these projects on  
275 lack of knowledge as the principal barrier to change therefore **often** limited their **capacity to realise**  
276 **broader recommended shifts in management and policy**. Cases also struggled to support emergent  
277 goals, such as addressing capacity needs. Effort to empower scientific knowledge risked  
278 marginalising the voices of other actors (and knowledge systems) who were excluded from the  
279 process but affected by resulting recommendations<sup>21</sup>.

280

### 281 **Mode 2**

282 **Empowering voices.** These cases also co-produced knowledge to address ecosystem management  
283 and policy challenges, led by interdisciplinary scientists alongside community and/or government  
284 actors. However, they differ from **mode 1** through **their explicit intention to empower** relatively  
285 marginalised **actors** and **include** greater social diversity, **such as by supporting initiatives of local and**  
286 **indigenous communities**. Cases created meaningful solutions for local actors and produced science to  
287 confront broader narratives that furthered ecosystem degradation and social inequalities<sup>43,59</sup>. Several  
288 cases navigated a careful balance between neither suppressing nor romanticising local views by  
289 developing respectful ways to integrate external expertise and expand problem definitions<sup>40,43</sup>.  
290 Compared with **mode 1**, cases emphasised process and more actively engaged with/in policy and  
291 management contexts, producing greater impacts<sup>57</sup>. Outcomes were enhanced for cases that prioritised  
292 process learning and quality, fulfilled capacity needs, and built institutions to evolve **multi-scalar**  
293 **partnerships and activities over time**. However, the strong emphasis on producing and empowering  
294 particular knowledge forms constrained possibilities for reframing. This knowledge could also be  
295 ignored by higher level decision-makers who were often not deeply involved, hindering **initiatives'**  
296 **broader desired social equitability outcomes**.

297

### 298 **Mode 3**

299 **Brokering power.** This **mode** was the smallest, **and** highly unique. Both cases engaged relatively  
300 powerful actors to develop long-term innovative institutions to address sustainability challenges. In  
301 contrast to **modes 1 and 2**, these cases fostered *dialogue around synthesised knowledge* and took  
302 direct policy and management actions, instead of mainly *producing scientific knowledge*. Both cases  
303 also equally focused on reframing problems *and* pursuing solutions, yet did so in distinct ways. One  
304 case created a safe space for international CEOs and scientists to reframe views of ocean  
305 sustainability problems to develop governance solutions<sup>36</sup>. The other case took collective action to  
306 restore a polluted river, using a shared concern as a pathway to build trust and reframe polarised  
307 relations in a cross-border conflict<sup>38</sup>. These cases used third party brokers and carefully controlled  
308 participation to facilitate safe spaces for dialogue, given the high potential for conflicts among  
309 identities and interests. Tracking process results was critical to fostering ongoing engagement and  
310 navigating a balance between speaking the language of powerful actors while trying to reframe  
311 thinking. Due to the stronger emphasis on scientific/technical expertise (over local knowledge and  
312 concerns), these cases **risked** legitimising existing power relations.

313

### 314 **Mode 4**



315 **Reframing power.** These cases engaged both relatively marginalised *and* powerful actors (e.g. local  
316 communities, and national NGO and government actors) to reframe technocratic narratives and shift  
317 practices and policies that marginalise social concerns<sup>37,51,60</sup>. Like **mode 3**, they were led by  
318 researchers alongside relatively powerful practitioners. However, in contrast, researchers explicitly  
319 sought to shift power away from powerful actors and towards marginalised actors whose perspectives  
320 they explored using ‘relativist’ critical social science methods. As a result, some reframing of  
321 dominant perspectives occurred; however, cases struggled to create ‘safe enough spaces’<sup>29</sup> to do so.  
322 This was partly due to spanning multiple cultures, sectors, and identities during relatively short  
323 timelines<sup>37</sup>, and partly related to their emphasis on producing knowledge (like **modes 1 and 2**) and  
324 little focus on institution building (unlike **mode 3**). This shifted the balance of power towards  
325 researchers, who faced the challenge of keeping work critical of power relations, while also trying to  
326 relinquish power to solutions-oriented actors to foster practical relevance<sup>51,60</sup>. Only cases with strong  
327 existing institutional roots or multi-scalar networks managed to somewhat shift policy and  
328 practice<sup>37,60</sup>.

329

### 330 **Mode 5**

331 **Navigating differences.** This **mode** is distinguished from **modes 1-4** through a stronger emphasis on  
332 managing processes of relating together, learning, and empowerment over producing and transferring  
333 scientific knowledge **about human-ecosystem interactions**. Researchers employed more ‘relativist’  
334 methods<sup>45</sup>, but in contrast to **mode 4**, they held less power. Facilitation techniques and boundary  
335 objects<sup>61</sup> were used to connect stakeholder groups to explore conflicts and reframe perspectives, while  
336 allowing new institutions, regulations, and practices to emerge. These processes valued all forms of  
337 expertise, and effectively minimised hierarchies to directly engage with actors across power  
338 differentials<sup>31</sup>. This model showed promising evidence of reframing, for example, by changing fixed  
339 notions of ‘stakes’ to more dynamic ‘stakeholding’<sup>34</sup> and shifting scientific knowledge from a  
340 dominant position to a more democratic one<sup>32</sup>. The early focus on reframing (instead of generating  
341 solutions) allowed actors to navigate conflicting identities to build long-term (mean of 8 years)  
342 complementary bottom-up and top-down processes<sup>32,42</sup>. This resulted in higher attainment of policy  
343 and management outcomes. Some cases additionally linked diverse local co-production efforts  
344 through learning networks<sup>34,35</sup>. A few cases were blocked by unsupportive high-level actors,  
345 underscoring the importance of managing those risks and building trust across power differentials.

346

### 347 **Mode 6**

348 **Reframing agency.** These cases focused the least on using co-production to solve pre-defined  
349 problems. Led mostly by researchers with **both** highly relativist design and systems thinking  
350 backgrounds, they created safe spaces to identify collective forms of agency capable of addressing  
351 systemic governance issues, such as through urban/transformation labs<sup>39,44</sup>. These cases did not seek  
352 to empower particular knowledge, but instead allowed diverse knowledge forms to be expressed. To  
353 create safe spaces, they engaged environmentally-motivated **change agents** in local contexts, thereby  
354 spanning fewer conflicting identities and cultures. They also explored emotional and psychological  
355 anxieties related to questioning power and beliefs<sup>39</sup>. Despite their relatively short duration, these cases  
356 most effectively triggered reframing, illustrating the value of creating spaces without explicit solution  
357 agendas. For example, in one case participants realised an incongruence between their own narratives  
358 and practices, leading them to shift focus from agro-technologies to fostering social solidarity<sup>44</sup>. These

359 cases also trained participants to employ co-production approaches in their own work. Few shifts in  
360 policy and practice have been documented; however, these projects did not explicitly seek these  
361 outcomes and also were among the most recently completed. These cases struggled most to engage  
362 powerful impact-motivated actors and risked creating echo chambers (i.e. spaces where people  
363 encounter views that mainly coincide with their own).

364

365 ----- INSERT FIGURE 5 NEAR HERE -----

366

### 367 **The outcomes and future of co-production for sustainability**

368

369 This analysis unpacks the diverse design and implementation choices that fall within the growing field  
370 of co-production scholarship and practice for [the sustainable development of ecosystems](#). The six co-  
371 production modes we identify show how distinct approaches to engaging with purpose, power,  
372 politics, and pathways are suited to achieving different types of outcomes. Yet, approaches also differ  
373 in their potential risks, such as creating echo chambers, reinforcing the status quo, and being co-opted  
374 by powerful vested interests (Fig. 5). By clarifying the connections between co-production choices  
375 and differential benefits and risks, we provide a heuristic tool to enhance understanding and design  
376 considerations where researchers and societal actors interweave knowledge and action for  
377 [sustainability](#). For example, among our cases, design choices that prioritised relating together and  
378 systemic interpretations of agency were crucial to reframing perspectives, while knowledge-focused  
379 and solution-oriented approaches were better suited to influencing policy. [Particular](#) approaches may  
380 also be appropriate in different stages of a change process, [and further research may explore the role](#)  
381 [of certain approaches in varying contexts](#)<sup>62</sup>. We therefore argue that this diversity is a strength –  
382 different approaches contribute to change in distinct ways, if the associated risks are proactively  
383 managed (Fig. 5).

384

385 In accordance with other studies<sup>13,16,63</sup>, our analysis shows that co-production requires careful  
386 facilitation to bridge diverse perspectives, values, and identities, and that multi-scalar and long-term  
387 engagement is essential for achieving outcomes (Fig. 6). Our cases collectively highlight just how  
388 varied the possible outcomes of co-production are, from informed policies and shifted narratives, to  
389 reshaped relations and institutions. Yet, particular synergies and trade-offs emerged among these  
390 outcomes (Fig. 6). For example, cases that fostered the most substantial reframing of perspectives and  
391 feelings of empowerment (e.g. in Reframing Agency) did not demonstrate shifts in policies or  
392 practices. Another notable trade-off is that the successful production of scientific knowledge was  
393 consistently negatively associated with attaining most other outcomes (Fig. 6). Similar to recent  
394 studies<sup>13,15,64,65</sup>, our analysis suggests that the tendency of researchers to direct co-production  
395 resources to filling knowledge gaps – whether led by natural scientists (e.g. in Researching Solutions)  
396 or critical social scientists (e.g. in Reframing Power) – may actually hinder the attainment of other  
397 types of outcomes that inspire collective action, such as reframing narratives and building institutions.

398

399 ----- INSERT FIGURE 6 NEAR HERE -----

400

401 Our study suggests that co-produced scientific knowledge can further *existing* policy goals; however,  
402 when the goal is to fundamentally *reframe* policies, we found that cultivating dialogue and relations

403 that question problem definitions and explore systemic forms of agency are critical (e.g. Navigating  
404 Differences & Reframing Agency; Fig. 4). Co-production efforts that demonstrated the largest shifts  
405 in institutions and management practices directly supported researchers and diverse societal actors to  
406 iteratively balance critically reflexive and solutions-oriented spaces (e.g. Brokering Power &  
407 Navigating Differences; Fig. 4). This allowed actors to navigate different agendas for change to grow  
408 ideas and actions which were unforeseen from the outset. While several local cases spanned these  
409 dual reflexive and action-oriented purposes of co-production, we call for greater exploration of how to  
410 do so across scales, and in particular with globally powerful actors.

411

412 Despite the promising outcomes of diverse co-production practices, their **ultimate sustainability**  
413 **impacts** remain unclear since few cases monitored **social** (13%) and **ecological** (22%) **aspects of**  
414 **sustainability, such as improved human well-being amidst more sustainable resource levels.**  
415 Attributing such impacts to co-production processes is challenged by their often spatially and  
416 temporally dispersed and unanticipated effects. We therefore support others' calls for approaches that  
417 iteratively monitor impacts occurring within (and not just after) co-production processes to support  
418 adaptive learning while acknowledging complex and unpredictable impact pathways<sup>1,9,12,19,66</sup>. Indeed,  
419 such monitoring was linked to enhanced achievement of outcomes across our cases (Fig. 6). For  
420 example, one case examined people's cognitive maps, perception of agency, and social networks at  
421 multiple stages during the process to facilitate *and* document the changes occurring<sup>44</sup> (see  
422 Supplementary Table 4 for more approaches). We therefore echo existing concerns that funding  
423 paradigms and policy orientations requiring predefined problem definitions and impact pathways may  
424 constrain the full range of possible outcomes of co-production<sup>5,66</sup>.

425

426 Undertaking this analysis enabled us to collectively and critically interrogate the diverse assumptions  
427 behind the purpose of our co-production practices, ways of navigating power and politics, and  
428 presumed pathways to sustainability. We have produced a heuristic that can be used to support  
429 researchers and practitioners to navigate the trade-offs and risks associated with different approaches  
430 to weaving knowledge, action, and change. Given similar co-production challenges around power,  
431 impact, and scale experienced across diverse fields<sup>1,4,13,21,63</sup>, this tool may help facilitate critical  
432 reflection in other contexts, or otherwise inform the design of additional analyses that go even further  
433 in depth and wider in scope. We encourage the application of our heuristic as a reflexive tool to open  
434 up dialogue and strengthen transparency in design choices in co-production processes for  
435 sustainability, and welcome future evaluations of its effectiveness for guiding scholarship and  
436 practice.

437

438

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440

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614  
615

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617

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637

## 638 **Author Contributions**

639

640 J.M.C., C.W. and M.R. conceived the project and co-led the design of methods, with contributions  
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643 coordinated the study, gathered all data, and led the data analysis in collaboration with all authors.  
644 J.M.C. and C.W. drafted the manuscript and all authors contributed and commented on drafts and the  
645 final version.

646

## 647 **Competing Interests**

648

649 The authors declare no competing interests.

650

## 651 **Figure Captions**

652

653 **Figure 1. Overview of the 32 cases.** Cases are grouped by the scale(s) at which the co-production  
654 work took place, while the map shows [the geographical](#) locations. Colors indicate the [mode](#) identities  
655 in Fig. 3. Listed contributors provided case materials and interviews, and held a senior leadership  
656 position in the case and/or extensively researched it. Additional case details are available in  
657 Supplementary Table 1. See Methods for details on the case selection process.

658

659 **Figure 2. Eight key differences in how cases approach co-production.** The number of cases that  
660 exhibited each approach at varying strengths is shown (lightest shade = no emphasis; darkest shade =  
661 very strong emphasis); E.g. 4 cases heavily focused on solving predefined problems, whereas 1 case  
662 did not define any solutions at the start. The correlations diagram shows the key tensions between  
663 blue and orange approaches, meaning that cases rarely managed to strongly employ both. See  
664 Methods for the scoring process of these approaches (dimensions) and Supplementary Table 2 for  
665 detailed 7-pt likert scale definitions and illustrative quotes.

666

667 **Figure 3. Six modes of co-production identified by approaches to purpose, power, politics and**  
668 **pathways.** Spider diagrams show the value of each of the 8 approaches for all case members of each  
669 mode. Case IDs and mode colors correspond to those in Fig. 1, demonstrating the high geographic  
670 and scalar diversity within each mode. See Methods for further details on the Hierarchical Clustering  
671 process.

672

673 **Figure 4. Comparison of co-production modes by main features and outcomes.** The +/- symbols  
674 indicate which mode means are significantly higher/lower for each dimension, with the overall  
675 significance of comparisons denoted (Kruskal-Wallis tests; <sup>†</sup>p < 0.10, \*p < 0.05, \*\*p < 0.01, \*\*\*p <  
676 0.001). For example, modes 1, 2 and 4 achieved more knowledge production, whereas modes 5 and 6  
677 achieved more reframing. Mode 3 rarely exhibited statistically significant differences due to its small  
678 size. Outcomes are grouped into intercorrelated sets (see Fig. 6). Results are grayed out when missing  
679 >50% of data for modes with 7-8 cases, and >25% data for modes with 2-4 cases. Descriptive  
680 dimensions that did not exhibit notable differences are not shown. See Supplementary Tables 3 & 4  
681 for definitions of all descriptive and outcome dimensions, respectively, and Supplementary Fig. 1 for  
682 correlations among all descriptive dimensions.

683

684 **Figure 5. The unique opportunities and critical risks of different modes of co-production.** When  
685 co-production initiatives strongly express particular combinations of approaches to purpose, power,  
686 policies and pathways, they hold unique ability to achieve certain outcomes, but each approach is also  
687 linked to critical risks. For example, mode 1 (researching solutions) and 6 (reframing agency) face the  
688 opposite transformative potentials and risks. The ability of modes 3 and 5 to achieve multiple types of  
689 outcomes (see Fig. 4; e.g. reframing, networks, management practices, institution building) is related  
690 to their unique ability to span the dichotomies: purpose (problem solving *and* problem reframing) and  
691 politics (influence powerful *and* empower marginalised), respectively. In contrast modes 1 and 6  
692 achieved fewer types of outcomes (see Fig. 4).

693

694 **Figure 6. Dimensions most strongly associated with higher attainment of sustainability**  
695 **outcomes.** The green/pink grid shows how achieving some outcomes is positively/negatively linked  
696 to achieving other outcomes (\*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001). Knowledge production is the only



697 outcome that is not correlated with achieving any other outcomes, and even shows a consistent  
698 negative trend. The descriptive dimensions that are most strongly correlated with each sub-group of  
699 intercorrelated outcomes are listed in the gray boxes. The white box contains all dimensions that are  
700 significantly linked to higher attainment of outcomes across the board. The definitions for all  
701 descriptive and outcome dimensions, and common methods that cases used to assess them are  
702 available in Supplementary Tables 3 and 4, respectively.

703

## 704 **Methods**

705

706 This study was [collaboratively produced](#) by contributors of the 32 cases through an iterative exploratory and  
707 analytical process during 2017 – 2019. We took a dialogical approach<sup>67</sup> in the overall study design by  
708 deliberately iterating between analysis conducted by the lead author and interrogation of those analyses by case  
709 contributors over multiple stages (further described below). This allowed the lead author to maintain  
710 independence of interpretation by individually conducting all interviews and empirical analyses, while  
711 conceptual framings and analytical interpretations of the study were iteratively improved by the in-depth  
712 practical knowledge of the diverse range of co-production experts involved. Workshops were organised at two  
713 different stages of the analysis to also foster an interactive space to co-develop the focus, scope, and methods for  
714 the analysis (further described below). This iterative multi-stage analysis resulted in a highly robust  
715 methodological approach to advance collective knowledge around diverse co-production framings, approaches,  
716 and outcomes. Our choice to [collaboratively produce](#) this research is consistent with a growing number of  
717 scholars who underscore the importance of [researchers producing knowledge with](#) those who are actually  
718 implementing the work under study in order to produce rigorous knowledge of important practical  
719 experiences<sup>68,26</sup>.

720

### 721 **Collaboratively produced common inquiry framework**

722 The research began with two participatory workshops, one convened at The Pew Charitable Trusts in  
723 Washington D.C., United States (May 23-25, 2017) and the other at the 2<sup>nd</sup> Programme on Ecosystem Change  
724 and Society (PECS) Conference in Oaxaca, Mexico (November 11-12, 2017). A number of scholars and  
725 practitioners working on different aspects of ‘co-production’ were invited to the Pew workshop, while  
726 participants self-selected into the PECS workshop, based on their interest and prior experience working on co-  
727 production. In these workshops, we grounded our analysis in the experience of the co-production cases. Case  
728 contributors responded to a series of open questions regarding co-production aims, practices, and outcomes,  
729 followed by participatory exercises to identify key differences and common challenges. The 25 participants in  
730 these workshops collectively represented more than 200 years of cumulative practical experience managing co-  
731 production initiatives for [the sustainable development of ecosystems](#) in 15 countries. Participants were diverse  
732 in terms of career stage, disciplinary background, and position, with half based in research institutes, and nearly  
733 all in positions operating at the interface of research and policy/practice (i.e. “scholar practitioners”). However,  
734 participants were predominantly women (80%) living in the Global North (85%), which undoubtedly shaped the  
735 discussions in the workshops. In an effort to rectify these biases, we subsequently conducted a wider review of  
736 relevant co-production literature to further develop the emerging common inquiry framework (i.e. a spreadsheet  
737 to inquire about important differences across diverse co-production cases) to guide subsequent data collection  
738 and analyses.

739

### 740 **Systematic case selection**

741 The 32 cases included some from the initial workshops (n=8) and others subsequently identified using Google  
742 Scholar (n=24). Our sampling approach followed an information-oriented, maximum variation approach to  
743 sampling – we selected cases [that would give the greatest possible information about co-production for the](#)

744 sustainable development of ecosystems – a sub-group in the domain of co-production for sustainability<sup>30</sup>. This  
745 selection strategy provided analytical power for exploring how different co-production aims, features, practices,  
746 and outcomes are interlinked. To select a broad range of cases, we chose to maximise diversity for sectoral  
747 involvement, the role of researchers, co-production practices, and geographical/scalar locations. While our  
748 sample has proven effective for identifying patterns, including the six modes of co-production, it has inherent  
749 limitations for attempting hypothetico-deduction. For example, we cannot determine which of these modes is  
750 more prevalent across the whole population of co-production for the sustainable development of ecosystems, or  
751 sustainability more broadly; nor can we draw general conclusions about the cause-effect linkages between  
752 modes and outcomes. A larger stratified random sample would be more effective for such purposes.

753

754 The eight cases selected from the workshops had been running for longer than 2 years and employed different  
755 co-production approaches to address challenges related to the sustainable development of ecosystems. The  
756 Google Scholar searches individually paired 10 ecosystem-focused variants of the term ‘sustainability’ such as  
757 ‘social-ecological’, ‘ecosystem services’ and ‘marine conservation’ with 22 variants of ‘co-production’ such as  
758 ‘co-design’, ‘co-management’, ‘social learning’, ‘action research’ and ‘transdisciplinary’ (see Supplementary  
759 Table 5 for a complete list of search terms). The co-production terms were selected by identifying key  
760 terminologies that appeared in co-production literature<sup>1,13,14,16</sup>. The range of sustainability and co-production  
761 terms ensured our selection of co-production initiatives that encompassed the diversity of approaches and  
762 contexts we found in the literature. Since we used Google Scholar to expand the diversity of our initial set of  
763 cases, our sample is biased towards co-production cases published in international peer-reviewed journals, as  
764 this work is more likely to be well known and highly cited. We set a clear ‘co-production’ boundary for our set  
765 of cases by excluding cases that were captured by our search terms, but were not interweaving knowledge,  
766 action and change. For example, collaborative governance interventions were only included in this study if they  
767 interweaved knowledge, action and change among participants; this meant excluding NGO or state led  
768 participatory interventions that did not involve researchers.

769

770 Despite the leading role of researchers in many cases, we sought to gather cases that spanned diverse research  
771 roles, from practitioners conducting knowledge synthesis, to researchers generating knowledge or facilitating  
772 dialogue. It was also difficult to engage local projects led by non-English speakers who do not have  
773 international networks. We therefore actively sought to include cases from a diverse range of contexts, with  
774 multiple cases in each broad geographical region, to incorporate some degree of cultural diversity. We  
775 acknowledge, however, that we first prioritised diversity in terms of co-production approaches, and only one-  
776 fifth of our sample is both located in the Global South *and* led by citizens of those countries. We therefore  
777 underscore the need for further work to examine approaches to co-production led by citizens of the Global  
778 South. Only three potential case contributors that we contacted declined to be involved in the project.

779

#### 780 **Data collection**

781 Applying the common inquiry framework developed in the initial stage of the research, we collected the  
782 following qualitative data for each case: 1) how co-production and sustainability challenges are framed, 2) how  
783 co-production is designed and implemented in practice, 3) the rationales underpinning decisions on how to co-  
784 produce, 4) capacities which support or hinder co-production, and 5) outcomes of co-production. The lead  
785 author (J.M.C.) completed a qualitative spreadsheet in partnership with a key representative of each case. For 29  
786 cases, this was a senior leader in the co-production process, while for 3 cases, this was someone who had  
787 extensively researched the case. The lead author interviewed most case representatives for approximately an  
788 hour to gather further qualitative information related to written responses in the spreadsheet. In a few cases, this  
789 was not necessary, as we gained sufficient case detail through email correspondence. To understand a broader  
790 range of perspectives of people involved in each project, we also reviewed a mean of 6 documents and  
791 publications per case (186 total), reviewing a greater number if the case was not yet published in peer-reviewed

792 literature. The lead author worked individually with each case contributor (an expert in the particular co-  
793 production process) to gather relevant and reliable materials to inform interpretations of the case, which spanned  
794 a mixture of scientific articles, grey literature, and internal documents. To ensure a robust assessment of  
795 outcomes across different forms of evidence, the lead author scored the quality of the evidence for each reported  
796 outcome by each case, and consulted with the case contributor to ensure further evidence was unavailable. The  
797 22 missing data squares in Fig. 4 reflect the exercised judgment of the lead author that the quality of evidence  
798 was insufficient to substantiate claims regarding those outcomes. Given the sensitive nature of reporting  
799 outcomes and case difficulties, to enhance open exchange and accurate reporting, case contributors were given  
800 the opportunity to indicate any parts of the data gathered about their project that they wish to remain anonymous  
801 in any outputs related to this project.

802

### 803 **Preliminary analysis and testing of dimensions of difference**

804 The lead author (J.M.C.) conducted a preliminary analysis by qualitatively coding each of the five  
805 aforementioned categories of data using NVivo Software, grounded in the data from and understanding about  
806 each case from the case contributors<sup>69</sup>. Two rounds of coding of the common inquiry spreadsheets (completed  
807 for each case) and additional case documents and interviews led to the identification of numerous qualitatively  
808 described dimensions of difference across all cases. These dimensions captured how the sample of co-  
809 production cases varied in how they were framed, designed, implemented, supported by certain capacities, and  
810 pursued and produced particular outcomes. These findings were then presented in a 13,000-word report and  
811 interrogated in an interactive two-day workshop in Colorado, United States (July 16-17, 2018) with 14 case  
812 contributors and experts in co-production. Participants discussed the content and framing of the dimensions  
813 through dynamic exercises, identified if important aspects were missing, and elaborated questions and methods  
814 for further analysis. A subsequent half-day workshop was held with 15 practitioners/researchers in Cambridge,  
815 United Kingdom (August 9, 2018) to explore the relevance and framing of the emerging list of dimensions of  
816 difference across cases with people who were generally not as familiar with co-production terminology and  
817 approaches. A final list of 72 specific dimensions therefore emerged from a rigorous iterative process that  
818 inductively identified critical points of difference across all cases.

819

### 820 **Secondary analysis based on final analytical dimensions**

821 The final list of 72 dimensions of difference across all cases guided the secondary analysis. The dimensions  
822 used in this analysis include different ways that co-production cases were framed (8), designed (16), and  
823 implemented (16), capacities that shaped how co-production cases functioned (4), and distinct outcomes that  
824 were intended (14) and produced (14). Each of the 14 outcomes were additionally scored on the extent to which  
825 they were assessed, if assessment had occurred. If the assessment method was evaluated by the lead author (in  
826 consultation with the case contributor) as being too poor of quality to assess particular outcomes, the  
827 achievement score was recorded as missing in the data set. Supplementary Table 4 presents the typical methods  
828 that were used to assess outcomes across the cases, including some of the most innovative approaches.

829

830 We employed fuzzy-set social science methods<sup>70</sup> to devise a scoring process to indicate the extent that cases  
831 exhibited particular dimensions. Fuzzy-sets provide a flexible approach for translating relevant and at times  
832 overlapping concepts that emerge from qualitative analysis into a quantitative framework that indicates the  
833 extent to which cases exhibit each feature (usually on a scale from 0-1)<sup>70</sup>. In this case, we found it was more  
834 straightforward to use a 7-point likert scale to define relevant steps for each dimension and then scored each  
835 case for each dimension. This allowed us to document step-wise differences, without needing to provide non-  
836 overlapping categories (i.e. exhibiting either one dimension or another, rather than some of each) that would  
837 lack precise meaning. To maintain a degree of independence of interpretation across all cases, for each of the 32  
838 cases, the lead author (J.M.C.) then reviewed all case documents and interviews an additional time to score each  
839 case on a 7-point likert scale for each of the 72 dimensions. A score of 1 indicated that the case did not exhibit

840 that dimension, whereas a score of 7 indicated that the case highly exhibited that dimension (e.g. for the  
841 dimension ‘intended networks’; 1 = no intention to reshape networks; 7; very strong intention to reshape  
842 networks).

843

844 Qualitative descriptions were recorded to justify each quantitative score, alongside illustrative quotes from case  
845 materials that further justified and explained those choices. Each case contributor reviewed and commented on  
846 the full set of scores and justifications/quotes to enhance the accuracy of the scoring process. The lead  
847 researcher also discussed dimensions that required further explanation with case contributors through a second  
848 hour-long skype call, or in a few cases, email correspondences. Following the revision of all scores and  
849 justifications, the lead researcher reviewed the qualitative descriptions for each numerical value of the likert  
850 scales to refine the precise meaning of each distinct step in all of the 7-point likert scales. Some case scores  
851 were then slightly adjusted according to the precise definitions to ensure consistency of the comparative scoring  
852 across all cases. The full list of definitions for all 7-point likert scales used in this analysis are available in  
853 Supplementary Tables 2, 3 and 4. The qualitative descriptions of all dimensions were coded and analysed in  
854 comparison to emerging literature on co-production approaches in order to identify the key dimensions of  
855 difference (the four ‘Ps’). Quotes also helped explain the patterns that emerged in the statistical analyses.

856

857 The [production](#) of this study by 42 people, many of whom are leading scholars in co-production and  
858 sustainability scholarship and practice, was essential for producing a salient and legitimate output that  
859 accurately reflects a rich breadth of co-production experience and perspectives. Moreover, many of the authors  
860 both conduct research on as well as practice co-production. Given the diversity of backgrounds, expertise,  
861 and experiences of the authors who [collaboratively produced](#) this study, a key component of the analysis  
862 focused on dialogue around different perspectives and approaches to co-production. This facilitated an  
863 analytical design that was both rigorous and reflexive, in which all co-authors were able to question their  
864 own views of co-production against others and draw collective insights.

865

### 866 **Statistical analyses**

867 All statistical analyses and visualisations were done using R version 3.6.1<sup>71</sup>. Given the large number of  
868 descriptive dimensions (36) and outcome dimensions (14 intended and 14 achieved), with substantial missing  
869 data for 5 achieved outcomes, we did not seek to determine causal patterns leading to specific outcomes. Rather,  
870 we sought to identify important differences in the overall designs/goals of co-production cases, and then use  
871 complementary quantitative and qualitative analyses to identify key features and broad patterns associated with  
872 the full range of outcome dimensions. Our secondary analysis and review of related literature identified four  
873 overarching themes (Fig. 2), with two alternate approaches to each, as being particularly important in directing  
874 projects towards different types of practices and intended outcomes. These alternate approaches to co-  
875 production for each theme are: for purpose, either to more effectively solve predefined problems, or to reframe  
876 problems; for power either focusing on the behaviour of actors directly linked to sustainability problems, or  
877 targeting more systemic aspects; for politics either empowering marginalised actors, or influencing powerful  
878 actors to yield power; and for pathways, either by primarily producing scientific knowledge as a product that is  
879 expected to shape policy and/or practice, or through more integrated forms of knowing, relating and doing.

880

881 To identify distinct modes of co-production, we conducted Hierarchical Cluster Analysis (HCA) using the eight  
882 approaches to co-production outlined above (and in Fig. 2). The NbClust<sup>72</sup> package in R identified six clusters  
883 as the optimal number, based on the peak of the Dindex second differences plot. The R Packages tidyverse<sup>73</sup>,  
884 cluster<sup>74</sup>, factoextra<sup>75</sup>, and dendextend<sup>76</sup> were used to conduct the HCA, using Euclidian distance as the  
885 dissimilarity matrix coefficient and Ward’s method of hierarchical clustering to minimise the error in sum of  
886 squares<sup>58</sup>. The R package fmsb<sup>77</sup> was used to generate the radar charts displayed in Figure 3. The R stats  
887 package<sup>71</sup> heatmap function was used to generate visual diagrams to show how case clusters differ (Fig. 4). The

888 qualitative descriptions associated with the scores for each case were also reviewed to help describe each cluster  
889 (i.e. mode). The qualitative analysis confirmed that all modes were well defined by important differences, and  
890 that even though one mode was especially small (#3), its highly unique nature merited its separation from other  
891 modes.

892

893 Unique features of each mode were examined by testing for significant differences between mode means for  
894 each descriptive dimension, using the stats package<sup>71</sup> to conduct Kruskal-Wallis tests. Pairwise Wilcoxon  
895 signed-rank tests revealed which pairs of modes were significantly different for each dimension. Relatively few  
896 significant differences emerged between mode 3 and other modes due to there being only two cases in the mode.  
897 To reduce the large number of descriptive dimensions, Principal Component Analyses (PCA) were conducted  
898 on three different sets of highly inter-correlated dimensions using R packages stats<sup>71</sup> and ggbiplot<sup>78</sup>. For  
899 example, the dimension ‘coproduced process’ is a principal component that explains 82.1% of the variance of  
900 the extent to which the case was co-designed and co-practiced. Similarly, the dimension ‘supportive context’  
901 explains 81.5% of the variance for two dimensions that indicate how well cases were supported by external  
902 funding and other contextual dynamics. Finally, the dimension ‘expertly facilitated’ explains 57.3% of the  
903 variance of nine highly intercorrelated dimensions related to the extent that cases organised roles, facilitated  
904 knowledge, and navigated issues of conflict and power.

905

906 The R packages qgraph<sup>79</sup>, SemiPar<sup>80</sup> and Hmisc<sup>81</sup> were used to visualise correlation networks among the eight  
907 key dimensions (Fig. 2). To explore correlations between achieved outcomes, we calculated Spearman’s Rank  
908 correlation coefficients and their p-values. For intended outcomes, we used the direct 7-point likert scale scores  
909 (see Supplementary Table 4). However, this was not possible for achieved outcomes because the meaning of an  
910 outcome that was highly achieved (i.e. score = 7) greatly varied for a case that highly intended that outcome  
911 versus one that weakly intended it and conducted few related activities. In order to calculate each achieved  
912 outcome, we therefore multiplied the extent to which it was achieved (e.g. score of 5 = 5/7) by the intention  
913 score (e.g. 5). In this way, a moderately achieved outcome that was highly intended was made equivalent to a  
914 moderately intended outcome that was highly achieved. To identify the list of nine descriptive dimensions  
915 significantly correlated to achieving outcomes across the board, we used the mean of eleven outcome  
916 dimensions, as three outcomes had insufficient data across cases.

917

#### 918 **Data availability**

919 The data analysed in this study can be made available upon request, with a few limitations. Quantitative data on  
920 outcomes cannot be shared at the level of individual cases because some projects are still ongoing, and some  
921 projects have not met their anticipated outcomes; thus, sharing this data could negatively impact projects and  
922 their participants. However, complete quantitative data can be provided at the level of each of the six modes,  
923 keeping the specific case identities anonymous. In addition, qualitative codes can be shared to provide further  
924 details of the qualitative analytical process.

925

926 At the level of individual cases, if people wish to access data for a specific case, they will be put in touch with  
927 the contributor of that case (also a co-author of this manuscript), who must be informed of the data being  
928 requested and the intended use for it. Each case contributor will then provide the final say on whether they wish  
929 to share their own quantitative and qualitative case data on a case by case basis. These protective steps were  
930 critical for ensuring a safe environment for case contributors to share many critical perspectives related to the  
931 challenges and outcomes of their cases, thereby ensuring an ethical analysis with accurate results.

932

#### 933 **Code availability**

934 The codes used in R to produce all statistics and figures can be made available upon request.

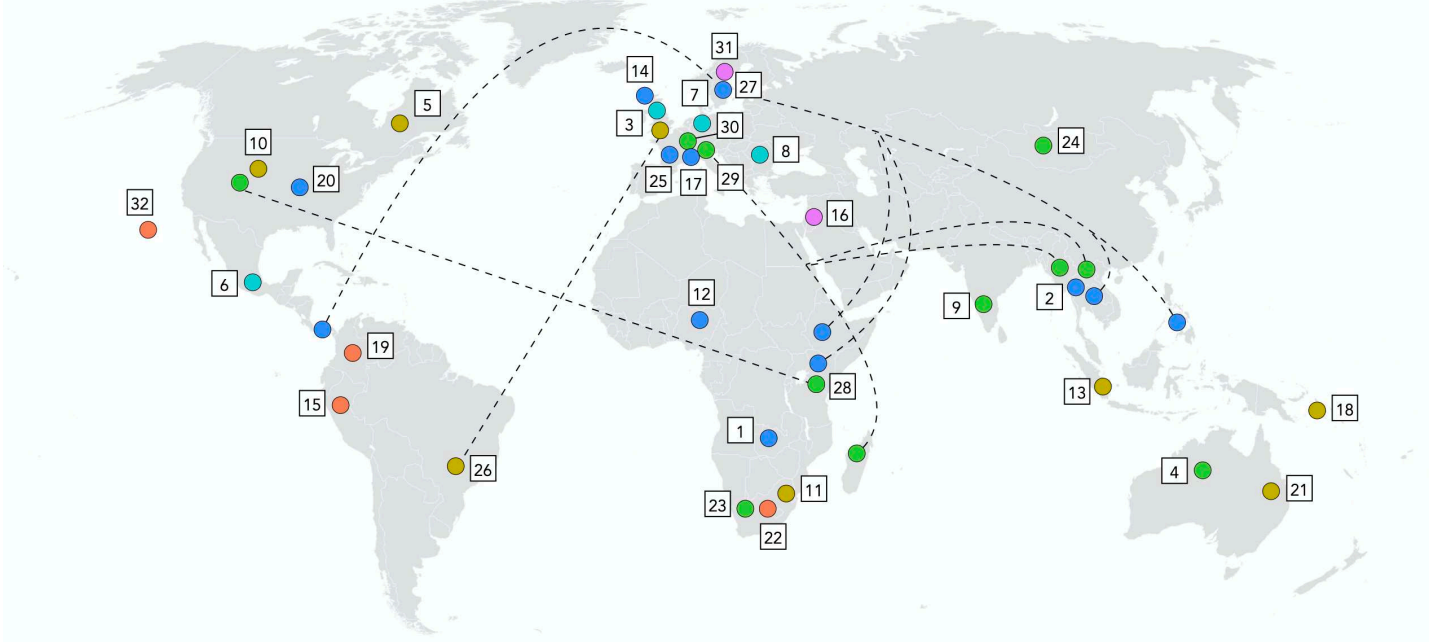
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






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**Ethics**

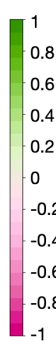
The institution that hosted this study (Luc Hoffmann Institute) does not have a formal research ethics approval process; however, we nevertheless developed our own procedure for this project, which complied with the Department of Geography Ethics Review Group guidelines at the University of Cambridge. Furthermore, all interviewees of this study are also co-authors on this manuscript, so they were involved in the decisions made throughout the entire process related to ethical concerns, with active steps taken to recognise their individual contributions, and to protect the confidentiality of their data. Each case contributor additionally communicated with the main proponents of their initiative to seek informed consent for the inclusion of the case in this research. In the majority of cases, case contributors were themselves a main project proponent, although in some cases, they had extensively researched it.

	<b>Id</b>	<b>Case description</b>	<b>Timeline</b>	<b>Contributor(s)*</b>
Mostly Local scale	1	Crafting local ownership of institution-building processes (i.e. Constitutionality): The case of the Kafue Flats fisheries in Zambia	2005-2010	Tobias Haller
	2	Gaming and simulation for co-learning to mitigate conflict and support collective action in Doi Tiew village, Northern Thailand	2007-2010	Pongchai Dumrongrojwattana
	3	Exploring radically different institutional personae to recast urban governance through co-production laboratories in Leeds, UK	2015-2017	Paul Chatterton
	4	Co-producing knowledge to manage Indigenous lands under a changing climate with an Arrernte community in Northern Australia	2013-2019	Rosemary Hill
	5	Montérégie Connection: Developing ecosystem models to improve land management in Mont-Saint-Hilaire, Quebec	2011-2014	Elena Bennett
	6	Promoting agency for social-ecological transformation through a Transformation-Lab in Xochimilco, Mexico City	2016-2019	Lakshmi Charli-Joseph
	7	Favourite places: Exploring emotional responses to landscape change in Oldenburg, Germany through social landart (land art)	2017-2018	Maraja Riechers
	8	Amplifying sustainability initiatives in Southern Transylvania through strengthening networks and analyzing leverage points	2016-2019	Andra Horcea-Milcu
Sub-national & Local	9	Assessing the socioeconomic and environmental implications of land sharing and land sparing strategies in the Western Ghats	2013-2018	Anca Serban
	10	Developing climate scenarios and ecological response models to build social-ecological climate resilience in Colorado, US	2013-2018	Renee Rondeau & Carina Wyborn
	11	Building the Durban Research Action Partnership to improve local land-use planning and management around Durban, South Africa	2011-pres.	Jessica Cockburn
	12	GyaraYankari: Establishing inclusive participatory protected area management in Yankari Game Reserve, Nigeria	2016-2018	Salamatu Fada
	13	Co-producing knowledge to develop and negotiate payment for watershed services schemes in Indonesia	2012-2015	Beria Leimona
	14	Probing the cultural depths of a nature conservation conflict in the Outer Hebrides, Scotland	2009-2015	Ruth Brennan
	15	Reframing 'win-win' conservation and development theory and practice with conservation organizations in northeast Peru	2013-2019	Josephine Chambers
	16	Alexander River Restoration Project: Restoring a heavily polluted river and fostering cooperation across the Israel-Palestine border	1995-pres.	Amos Brandeis
National, Sub-national & Local	17	Chasseral Regional Nature Park: Top-down and bottom-up institution building for landscape management in Switzerland	1997-pres.	Jean-David Gerber
	18	Improving the uptake of climate models by South Pacific communities and NGOs to build adaptive capacity to climate change	2013-2014	Chris Cvitanovic
	19	Future-Proofing Conservation: Enabling adaptive governance in Colombia's protected areas amidst climate uncertainty	2015-2018	Claudia Munera & Carina Wyborn
	20	Enhancing fire-adaptation capacity at multiple scales in the US through The Fire Adapted Community Learning Network (FAC-NET)	2013-pres.	Bruce Goldstein
	21	eWater Cooperative Research Centre: Developing a national eco-hydrological modeling and decision support platform in Australia	2005-2012	Melanie Ryan
	22	Addressing the socio-ecological impacts of conversions to game farming amidst post-Apartheid conflicts and power imbalances	2007-2014	Marja Spierenburg
	23	Co-producing knowledge and spanning boundaries to promote implementation of freshwater conservation plans in South Africa	2008-2012	Jeanne Nel
	24	Mongolian Rangelands and Resilience (MOR2) Project: Examining pastoral social-ecological systems in rural Mongolia	2008-2015	María Fernández-Giménez
Global & Other scales	25	SLIM project: Analyzing and developing social learning processes for integrated water management in 12 sites across Europe	2001-2004	Patrick Steyaert
	26	Contacted: Developing a science-policy-practice framework to reduce environmental risks from production and trade of soy in Cerrado, Brazil	2014-2018	Paz Durán, Jonathan Green & Angela Guerrero
	27	Connecting diverse knowledge systems at multiple scales in IPBES assessments and related science-policy contexts	2011-pres.	Maria Tengö
	28	Using science to support community-level and national-level action on conservation and pastoral development issues in East Africa	1999-pres.	Robin Reid & Kathleen Galvin
	29	Innovating to secure ecosystem services and well-being in telecoupled landscapes in Madagascar, Myanmar and Laos	2015-2020	Julie Zähringer
	30	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES): Strengthening science-policy interfaces	2012-pres.	Jasper Montana
	31	SeaBOS, emerging from Keystone Dialogues: Connecting science with global seafood industry leaders for ocean stewardship	2012-pres.	Henrik Österblom
	32	Developing a global think tank to address the human dimensions of Large Scale Marine Protected Areas (LSMPAs)	2014-2017	Nathan Bennett

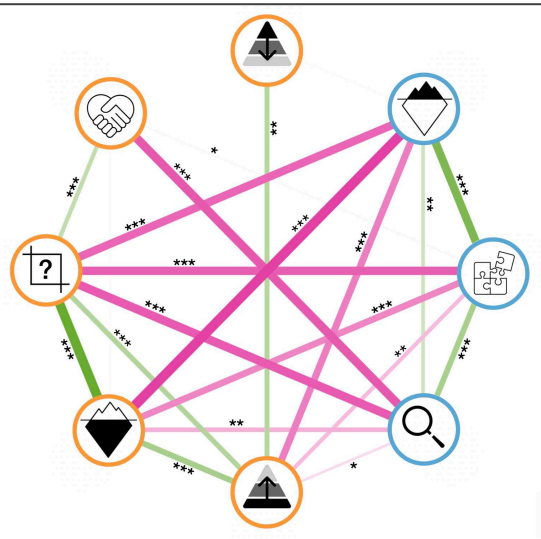


Theme	Approach
<b>Purpose</b> Why do actors co-produce?	<b>To solve problems</b> 1 5 2 5 6 9 4 Extend the case uses co-production to pursue solutions to problems defined near the beginning 
	<b>To reframe problems</b> 0 3 3 3 8 5 10 Extend the case actively facilitates reframing of views of problems and solutions during co-production 
<b>Power</b> How is human agency conceptualised?	<b>Shaping direct agency</b> 3 2 8 4 5 6 4 Extend the case focuses on changing the behaviour of actors directly linked to sustainability problems 
	<b>Shaping systemic agency</b> 1 2 3 4 10 6 6 Extend the case focuses on challenging paradigms and goals at higher governance scales 
<b>Politics</b> How are power relations changed?	<b>Influencing powerful actors</b> 2 4 9 9 8 0 0 Extend the case engages powerful actors to reduce their own and peers' power over marginalised actors 
	<b>Empowering marginalised actors</b> 1 8 3 5 11 3 1 Extend the case engages marginalised actors to iteratively shift power relations with powerful actors 
<b>Pathways</b> How are impacts catalysed?	<b>By producing knowledge</b> 2 4 4 4 6 6 6 Extend the case relies on expected transfer of scientific knowledge products to generate intended impacts 
	<b>By relating together</b> 0 1 6 8 3 6 8 Extend the case focuses on relating and doing together to create space for emergent outcomes 

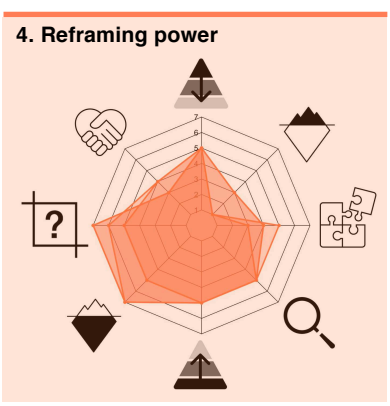
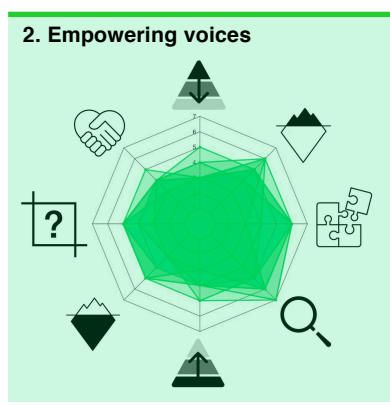
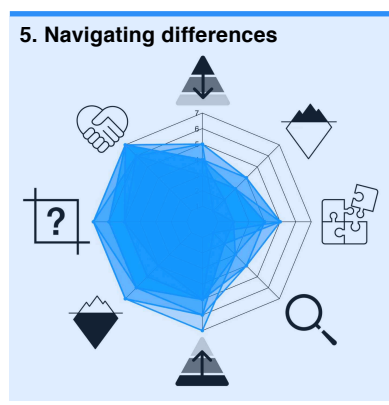
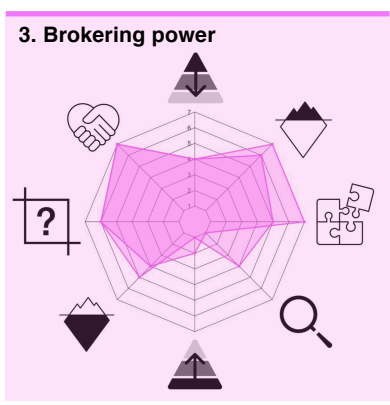
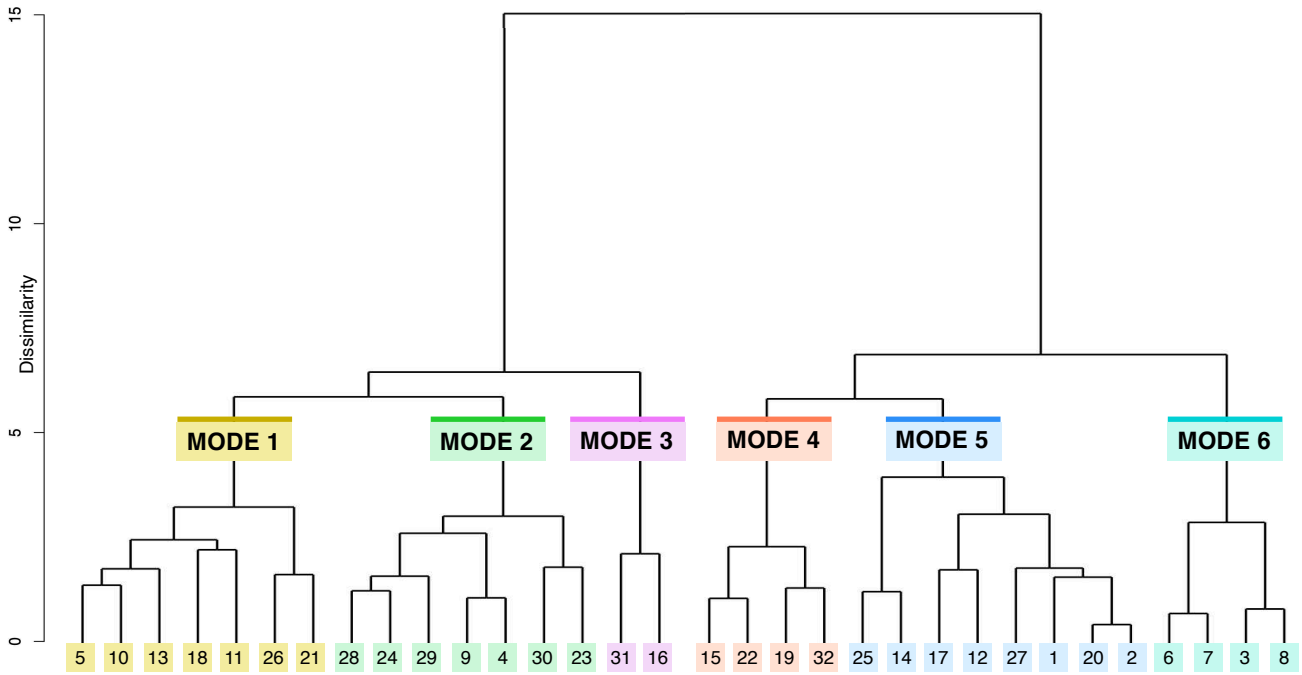
**Dimension relations**



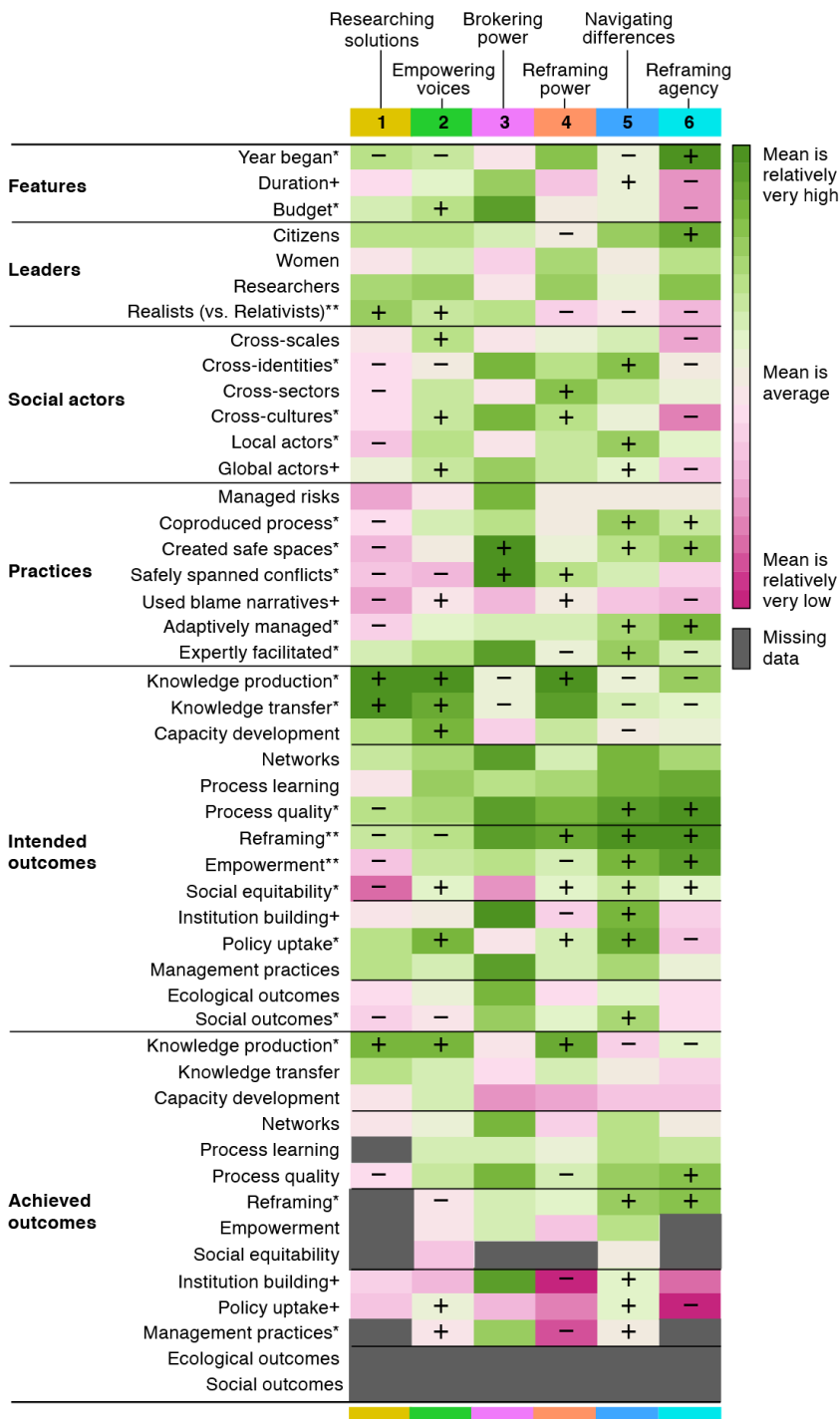
\* p<0.05  
 \*\* p<0.01  
 \*\*\* p<0.001













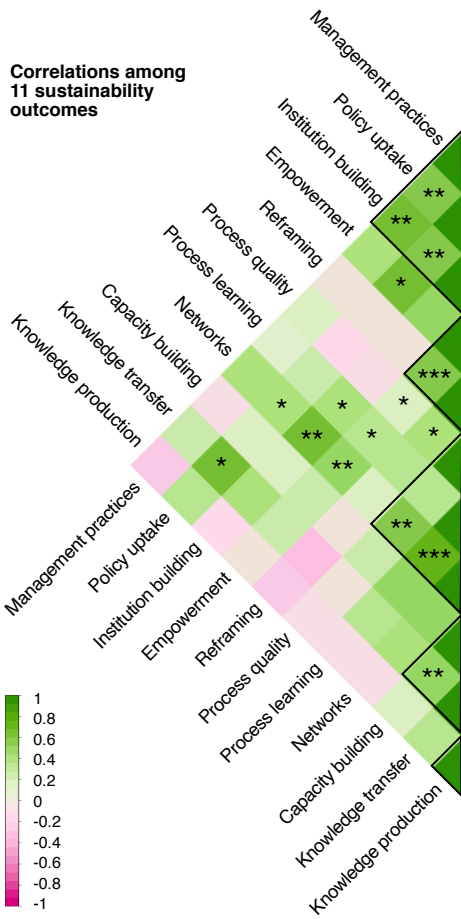


<u>Purpose</u>	<u>Power</u>	<u>Politics</u>	<u>Pathways</u>
Solve problems	Direct agency	Influencing powerful	Producing knowledge
Reframe problems	Systemic agency	Empowering marginalised	Relating together



Clusters	Approach	Unique opportunities	Critical risks
Researching solutions Empowering voices	 <b>Direct agency</b>	<i>Can achieve specific set goals (e.g. building an ecosystem model)</i>	<ul style="list-style-type: none"> <li>• More likely to overly place blame on marginalized actors for sustainability problems</li> <li>• Less attention to process and equitability can result in superficial engagement with marginalized actors</li> <li>• Interventions may legitimize existing power relations and systems</li> </ul>
	 <b>Solve problems</b>	<i>Can produce and transfer knowledge to inform and justify policy changes that decision-makers already want to make</i>	<ul style="list-style-type: none"> <li>• Projects may struggle to engage actors that they seek to influence due to prioritizing their own values and solutions</li> <li>• More likely to reinforce already dominant views of problems and solutions and to obscure alternatives</li> <li>• Can inhibit the potential to reframe perspectives</li> </ul>
	 <b>Producing knowledge</b>	<i>Can produce and transfer knowledge to advocate for higher level policy changes, build capacities, and address local needs</i>	<ul style="list-style-type: none"> <li>• May create echo chambers that fetishize the power of knowledge to create desired impacts</li> <li>• Emphasis on the value of scientific knowledge can crowd out alternative expertise and ideas</li> <li>• Tying of budgets to fixed knowledge production activities may inhibit the pursuit of emergent goals</li> </ul>
	 <b>Empowering marginalised</b>		<ul style="list-style-type: none"> <li>• May fetishize the role of speaking 'truth' to power to shift higher level views and policies</li> <li>• Efforts to empower particular views can inhibit possibilities for reframing perspectives</li> <li>• Powerful actors may block processes that are against their interests, especially if blame narratives are used</li> <li>• May overlook power imbalances and politics occurring within local settings</li> </ul>
Reframing power	 <b>Systemic agency</b>	<i>Can fundamentally shift views to co-develop more creative and transformative possibilities</i>	<ul style="list-style-type: none"> <li>• Expanding the problem frame can disempower actors if problems then feel too 'big' to handle</li> <li>• May be less effective if emotional aspects such as anxieties about losing power are not addressed</li> <li>• Efforts that span few identity conflicts and power differentials can result in echo chambers</li> <li>• May result in talk shops that don't produce action</li> </ul>
	 <b>Reframe problems</b>		<ul style="list-style-type: none"> <li>• Solution-oriented actors may not want to engage</li> <li>• Reflexivity can inhibit developing concrete actions</li> <li>• Successful reframing alone may fail to trigger shifts in policies and practices</li> <li>• Emphasizing points of difference too soon can inhibit common ground</li> </ul>
	 <b>Relating together</b>	<i>Can build legitimate and flexible processes to empower tangible changes to perspectives, networks, institutions, policies, and practices</i>	<ul style="list-style-type: none"> <li>• Apparent cooperation and consensus can be the result of subjugation if power dynamics are poorly managed</li> <li>• Social inequalities may be accelerated if voluntary contributions are not suitably valued</li> </ul>
	 <b>Influencing powerful</b>		<ul style="list-style-type: none"> <li>• Very risky without high legitimacy, strong networks and highly skilled facilitation and brokering to create safe spaces for reflection and dialogue</li> <li>• Actors involved may try to co-opt the process to serve their own interests</li> <li>• Exclusion of marginalized actors may lead to solutions that further marginalize them</li> </ul>
Brokering power	Navigating differences Reframing agency		

**Correlations among 11 sustainability outcomes**



**Descriptive dimensions positively correlated to groups of outcomes**

- Supportive context\*\*\*
- Duration\*\*\*
- Budget\*\*\*
- Used constructive narratives\*\*
- Co-produced process\*\*
- Global actors\*\*
- Cross-scales\*\*
- Co-produced process\*\*\*
- Relating together\*\*\*
- Reframe problems\*\*
- Created safe spaces\*\*
- Adaptively managed\*\*
- Social cohesion / trust\*\*
- Co-produced process\*\*\*
- Expertly facilitated\*\*\*
- Relating together\*\*
- Adaptively managed\*\*
- Monitored outcomes\*\*
- Used constructive narratives\*\*
- Social cohesion / trust\*\*
- Supportive context\*\*
- Monitored outcomes\*\*\*
- Knowing together\*\*
- Realists (vs. relativists)\*\*
- Knowing together\*\*\*

**Descriptive dimensions negatively correlated to groups of outcomes**

- Year began\*\*
- Knowing together\*\*
- Cross-identities\*\*
- Relating together\*\*\*

**Dimensions significantly linked to higher attainment of outcomes across the board**

1. Highly collaboratively designed and practiced process (co-produced process\*\*\*)
2. Very effective facilitation across social-political differences (expertly facilitated\*\*\*)
3. Very supportive funding arrangement and broader context (supportive context\*\*\*)
4. Extensive effort to monitor process and results oriented outcomes (monitored outcomes\*\*\*)
5. Strong levels of social cohesion and trust reached among actors (social cohesion/trust\*\*\*)
6. Use of narratives that frame issues constructively (use constructive narratives\*\*)
7. Engagement with actors that work at higher scales during the process (global actors\*\*)
8. Collaborative processes that continue to engage over long periods (duration\*)
9. Processes that connect work across local/regional and national/global scales (cross-scales\*)