



34 <sup>15</sup>*iDiv – German Centre for Integrative Biodiversity Research, 04103 Leipzig, Germany*

35 <sup>16</sup>*Urban Institute, ICOSS, The University of Sheffield, 219, Portobello, Sheffield, S1 4DP,*  
36 *United Kingdom*

37 <sup>17</sup>*School of Development, Azim Premji University, PES Campus, Pixel Park B Block, Hosur*  
38 *Road, Beside NICE Road, Electronic City, Bengaluru – 560100, Karnataka, India*

39 <sup>18</sup>*Institute of Environmental Science and Technology (ICTA), Autonomous University of*  
40 *Barcelona (UAB), CTA-ICP Building Z Campus UAB 08193 Bellaterra (Cerdanyola), Spain*

41 <sup>19</sup>*School of Public Affairs, University of Colorado Denver, 1380 Lawrence Street Suite 500,*  
42 *Denver, Colorado 80217, USA*

43

#### 44 **Abstract**

45 Institutions are vital to the sustainability of social-ecological systems, balancing individual  
46 and group interests and coordinating responses to change. Ecological decline and social  
47 conflict in many places, however, indicate that our understanding and fostering of effective  
48 institutions for natural resource management is still lacking. We assess theoretical and  
49 methodological challenges facing positivist institutional analysis, focusing on natural  
50 resource governance according to Ostrom’s social-ecological systems (SES) framework.  
51 Rather than adding more variables, progress requires a clearer, more consistent approach to  
52 selecting, defining and measuring institutional elements; stronger links between theory and  
53 empirical research; a greater focus on mechanisms and causality; and the development and  
54 application of new methods, including quantitative approaches. Strengthening the  
55 connections between theory, models, and data suggests several promising avenues for  
56 advancing institutional analysis through the study of relationships between institutional  
57 structure, process, function, context, and outcomes.

58

#### 59 **Introduction**

60 In our current context of global environmental change [1], the need for effective institutions  
61 (i.e., formal laws, rules, norms and customs [2]) to moderate human impacts, through

62 environmental governance and management, has never been greater. Institutions are essential  
63 to coordinate resource use across different jurisdictions, resolve trade-offs between individual  
64 and group interests, and allocate benefits and costs among actors [3-5]. While there are many  
65 approaches to institutional analysis and design (e.g., [6-9]), and some are incompatible with  
66 the perspective we adopt here, the strongest influence on environmental sustainability science  
67 has been the ‘Bloomington School’ [10], and particularly Ostrom’s IAD (Institutional  
68 Analysis and Design) and Social-Ecological Systems (SES) frameworks [11-14].

69         Despite its widespread use in environmental science, the application of the IAD/SES  
70 framework is limited by a set of theoretical and methodological challenges. Although  
71 research into environmental governance has identified many institutional characteristics and  
72 arrangements (or subsets thereof) that have proven effective at different scales [15-17],  
73 successful models of governance are often difficult to transfer across environmental issues,  
74 contexts or scales [18,19], suggesting that we do not fully understand how models of  
75 governance must change with context and scale. We first provide a short critique and then  
76 focus on challenges and new directions, proposing a post-Ostrom agenda for institutional  
77 research on natural resource governance as the study of the relationships between  
78 institutional structure, process, function, context, and outcomes (Box 1).

79  
80 **A Critique of Institutional Analysis in Social-Ecological Systems and Environmental**  
81 **Science**

82 Institutional analysis is central to understanding the management and governance of natural  
83 resources [3]. Institutional solutions for natural resource governance [20,21] highlight the  
84 importance of interactions among a wide range of social, ecological and institutional factors  
85 [22], and have contributed to analytical tools for interdisciplinary inquiry and empirical  
86 synthesis [11,23]. Theoretical and practical progress in SES analyses of institutions have,

87 however, run into barriers in recent years as scholars have struggled to connect high-level  
88 general principles and detailed case studies [24].

89         The Bloomington School has excelled at identifying salient features of SES  
90 governance, resulting in long lists of potentially influential factors; but has struggled to  
91 explain why, how, and under which social-ecological conditions specific institutional  
92 elements contribute to specific outcomes (as defined in Box 1) for at least three major  
93 reasons. First, despite repeated calls for coordination and integration [13,25], inconsistent  
94 definitions and measures of the elements in Box 1 continue. The SES framework was  
95 designed to address this challenge, but lacks definitions and measures for core concepts  
96 [14,26-29]. Further development is also needed in defining and categorising relevant  
97 outcomes, the processes and interactions that create them, and trade-offs.

98         Second, institutional analysis using the IAD and SES frameworks says little about the  
99 longer-term processes by which institutions emerge, change, and interact with resource use  
100 and management decisions. Ostrom's institutional design principles contribute to sustainable  
101 management in certain local contexts [15,30], but the pathways through which they are  
102 implemented, the relevance of history and path dependence (Epstein et al., this issue), and the  
103 role of embedded agency are poorly understood [31,32]. For example, decentralization  
104 programs for community-based management may fail if policymakers, bureaucrats or local  
105 elites respond strategically to maintain or enhance their influence over resources [33,34].

106         Third, institutional analysis using the IAD/SES framework has focused on local  
107 communities and resources, often neglecting broader scales (or occasionally, *vice versa*).  
108 Institutions at different scales often interact. For example, local depletion of resources can be  
109 driven by connections to global markets [35], which can have a range of broader impacts on  
110 other ecosystems [36]. Local framings may also ignore cross-scale power dynamics and the  
111 relationships between power, efficiency, sustainability, and effectiveness [37]. While the

112 notion of polycentric governance [38] formally recognizes the existence of multiple  
113 interdependent centers of decision-making, it has traditionally suffered from many of the  
114 same methodological challenges as institutional analysis [39,40].  
115 Key theoretical and methodological challenges relate to (1) specification (i.e., consistently  
116 describing, measuring, and relating the elements of institutional analysis across different  
117 studies and disciplines); and (2) causal relations (mechanisms) by which institutional  
118 elements of SESs influence outcomes over time.

119

## 120 **Theoretical Challenges for Institutional Analysis of Social-Ecological Systems**

### 121 *Specification*

122 Applications of Ostrom's SES framework generally take an *ad hoc* approach to selecting and  
123 defining variables, resulting in limited overlap between studies. Differences in measurement,  
124 terminology and definitions, and a lack of precision in concepts, measurements, and theory,  
125 threaten the validity of attempts to compare, contrast, or synthesize findings between studies  
126 [41].

127 A particularly important challenge is to define and measure environmental  
128 governance systems, which are heterarchies that incorporate elements of both networks and  
129 hierarchies [42,43]. Although they include a wide range of actors, networks, power relations,  
130 and tasks (e.g. rulemaking, monitoring, and maintenance), comparative empirical studies  
131 usually rely on binary measures of environmental governance, such as community vs.  
132 government-owned forests or presence/absence of local autonomy in making rules [44,45].  
133 This can result in the grouping of vastly different models. For instance, local autonomy in  
134 rulemaking might encompass decisions made by a single community or a group of  
135 communities in a system of nested governance; communities operating independently of  
136 other stakeholders; and communities that receive significant support from external partners.

137 Although a more precise understanding of relational structure is developing through network  
138 analysis [46], systematic coding of the attributes of institutional statements (i.e. formal and  
139 informal rules, norms and strategies) using the institutional grammar tool [47] and mapping  
140 of power relations [48], important gaps remain.

141         Second, while many theories of governance exist [49], few are specific enough to  
142 permit robust empirical tests or quantitative formalization. Both abstract theories about  
143 institutions and context-specific hypotheses derived from local case studies can be difficult to  
144 empirically operationalize and falsify [50]. For instance, institutional theory often highlights  
145 the importance of institutional fit, or matching institutions to the problems they are meant to  
146 address [51-53]. However, few theories explicitly identify the combinations of social and/or  
147 ecological conditions and the elements of institutions (Box 1) that give rise to fit.

148

#### 149 *Causal relations and dynamics*

150 Institutional theory analyzes the outcomes of institutions, but there is a growing demand for  
151 an improved theoretical understanding of the processes by which institutions emerge, change,  
152 and influence environmental outcomes [54]. The SES literature focuses on explaining system  
153 states and resource robustness (with exceptions; [3,55]), while feedback loops, historical  
154 influences, and changes in dynamics of power, culture, and beliefs that provide a broader  
155 social context often receive limited attention [48,56]. The same is true of the responses of  
156 institutional structures to ecological dynamics and uncertainty.

157         Second, additional challenges are raised by theories that endogenize the development  
158 of institutions. Environmental governance can involve many decision-making venues [5,57],  
159 tasks (e.g., enforcement, conflict resolution, environmental monitoring [58]), and competing  
160 interests [59], that interact with biophysical processes as well as technological expertise  
161 [29,60]. Three possible entry points into endogenizing the dynamics of these environmental

162 governance components include (i) the ecology of games, (ii) the network of action  
163 situations, and (iii) social-ecological network analysis.

164         The ecology of games framework [5,61] focuses on the structure, function and  
165 process of complex (e.g. polycentric) environmental governance. It has contributed to  
166 understanding decision-making, as well as the potential implications of participants,  
167 institutions and network structures for coordination and cooperation [62]. Nonetheless, by  
168 focusing on collective decision-making in multiple venues, the ecology of games framework  
169 typically does not clarify or trace the processes by which collective-choice decisions  
170 influence implementation and resource use.

171         The network of action situations approach [63] has been used to follow institutions  
172 from their development to their outcomes [54,64]. It has promise for understanding feedbacks  
173 and other dynamic elements of institutional change, but generally neglects the diversity of  
174 venues in which decisions are made, venue specialization around particular functions or  
175 action situations, and biophysical processes.

176         Social-ecological network analysis shows promise for understanding the implications  
177 of biophysical processes (e.g. fragmentation, dispersal) for environmental governance  
178 systems [65,66]; but the ways in which links are conceptualized typically vary across study  
179 systems, and ecological and/or social processes are often simplified, resulting in a loss of  
180 information about human-biophysical interactions [67]. In addition, although networks  
181 provide a context for an institution, the geographic and economic contexts of individual  
182 nodes and entire networks (e.g., location on an environmental gradient) are often ignored or  
183 hard to integrate. Network studies in SES research often lack a well-developed structure-  
184 function theory with associated methodology, making rigorous hypothesis development and  
185 testing difficult.

186           In sum, social-ecological outcomes emerge from the interplay of a wide range of  
187 processes [11]. These include (i) social processes by which actors interact (e.g. rulemaking,  
188 enforcement and conflict resolution); (ii) biophysical processes involving interactions among  
189 the natural and built components of ecosystems (e.g. predation, water flows through canals);  
190 and (iii) two-way, social-ecological interactions between actors and the natural and built  
191 environment (e.g. appropriation, monitoring, maintenance, recreation; [23]) over multiple  
192 spatial and temporal scales. While many of these processes are well-recognized in Ostrom's  
193 IAD/SES frameworks and related SES approaches, others (e.g., predation, ecological  
194 competition, non-extractive SES interactions) are not; and we lack a contextual  
195 understanding of their inter-relationships. Lessons learned in other fields (e.g., epidemiology,  
196 physics) suggest that a stronger interaction between empirical data and models may result in  
197 faster progress.

198

## 199 **Methodological challenges for institutional analysis of Social-Ecological Systems**

### 200 *Specification*

201 Differences in conceptualising and measuring institutions frequently result in  
202 incommensurable data, leaving findings open to interpretation and argument. Better  
203 coordination between researchers and the adoption of formal approaches, such as ontological  
204 databases designed for knowledge sharing and re-use, would facilitate translation and  
205 synthesis of case studies from different conceptual settings [68]; but three additional  
206 problems arise.

207           First, system structure is often weakly defined or undefined. Methods are needed to  
208 clearly define system boundaries and the relative placement of different actors in  
209 *heterarchical* systems of governance, including weak and informal ties that may nonetheless  
210 be vital during times of change or reorganisation [69]. Defining and bounding the study

211 system explicitly facilitates definition of ‘context’, and its role in constraining or confounding  
212 the relationships between institutional structure, process, function, and outcomes.

213         Second, institutional analysis often involves both aggregation and selection; the  
214 subjectivity of current approaches for aggregating and selecting study elements contributes  
215 further to our inability to compare between studies. And third, we lack rigorous approaches  
216 for measuring and comparing the roles of formal and informal rules (*de jure* vs. *de facto*).  
217 Promising quantitative approaches include multilevel networks, which consist of two or more  
218 separate but interconnected networks [70]; and multiplex/multilayer networks, which can  
219 incorporate heterogeneous nodes connected through different types of social and ecological  
220 relationships [71] or agent-based models [72].

221

## 222 *Causality and dynamics*

223         Institutional analysis in SESs faces practical difficulties (e.g., short-term funding,  
224 respondent attrition, career incentives and competition between researchers) in collecting  
225 long-term panel data. Ecologists have developed a range of long-term, broad-scale system  
226 manipulations and controls, as exemplified by fence-line contrasts, exclusion plots, and  
227 fragmentation experiments, to test hypotheses about the ecological components of SESs [73].  
228 Corresponding long-term observations and experiments treating institutions as elements of  
229 SESs are needed [74,75], although research on these themes must confront and resolve the  
230 ethical challenges of working on human subjects as well as methodological issues related to  
231 operating in complex adaptive systems [74]. Top priorities include methods and measurement  
232 of fast-changing process-related variables, such as perceptions, attitudes and certain kinds of  
233 behaviour [76], as well as environmental outcomes through time (and their interactions with  
234 social tradeoffs and outcomes) in a greater diversity of cases.

235           Second, the lack of a clear understanding of causality in SES institutional analysis  
236 makes it difficult to relate heterogeneity in institutional elements to outcomes. For example,  
237 greater actor diversity in decision-making may lead to more effective problem-solving, via a  
238 mechanism similar to that of natural selection; but tests of this hypothesis are easily  
239 confounded by the formal and informal institutions that guide decisions. Methods that can  
240 deal more effectively with heterogeneity in SESs are needed.

241

## 242 **New Directions and Opportunities for Institutional Research in Social-Ecological** 243 **Systems**

244 We perceive a strong need in SES research to (1) develop clear, fully specified models of the  
245 relationships between different institutional elements (Box 1); (2) use these to generate  
246 hypotheses about institutional emergence and influences on SESs; and (3) test such  
247 hypotheses systematically with data and models (Fig. 1). Several related avenues of enquiry  
248 again seem particularly important.

249           First, reliable generalisations about populations of cases depend on rigorous  
250 measurement. In ecology, which experienced similar problems [77], standard approaches to  
251 description and measurement (e.g., Linnaeus's taxonomy; areas of quadrats) were developed  
252 by deliberately testing and comparing alternative empirical approaches and their feasibility,  
253 cost, and associated errors. For institutions, the equivalent is to combine simulation models,  
254 case study data, and experiments (Fig. 2) over time and across levels and scales. One possible  
255 entry point for measuring governance systems as continuous entities is the concept of  
256 heterarchy, which unifies the perspectives of hierarchy (i.e., top-down or bottom-up controls)  
257 and network (i.e., peer-to-peer controls) in a single framework [43]. Analysts could use the  
258 heterarchical approach, for example, to compare and evaluate different types of polycentric

259 systems, catering for both hierarchies and networks in a single system [40], and thereby  
260 moving beyond normative prescription toward practical insight.

261         Second, system definitions must be consistent, while coping with change and  
262 transformation. At the very least, the analyst must know whether they are still working on the  
263 same system after a perturbation, intervention, or regime shift. System identity resides in the  
264 spatiotemporal continuity of key system elements and interactions [78]. Social-ecological  
265 identity can be measured both qualitatively (e.g., observations of customary practices) and  
266 quantitatively (e.g., proportion of community engaged in farming; area of forest) in relation  
267 to the subjective or normative goals of an analysis, and tracked through time [79].

268         Third, modelling approaches for understanding causality have been under-exploited in  
269 SES research, particularly in relation to understanding inconsistency in the outcomes  
270 resulting from individual institutions. In particular, we propose (i) using a diversity of theory-  
271 oriented and empirically-based models more deliberately to develop and test hypotheses; and  
272 (ii) clarifying the scope of generalizations by defining populations of relevant cases to which  
273 they apply. Theory-oriented or stylized models, which focus on key system components and  
274 interactions to develop principles of broad general relevance, are tools for both understanding  
275 causality and directing empirical research [80] and have additional value in clarifying  
276 concepts, framing potential outcomes and counterfactuals, and improving rigour. In SES  
277 research they can, for example, connect social and ecological dynamics via feedbacks [81], or  
278 be used to assess how theoretical understandings of human behaviour explain observations  
279 [82,83]. Models can and should guide theory testing [84]; while empirical research should  
280 generate and assess hypotheses that in turn drive new modelling enquiries. Clarifying the  
281 scope of generalisations about SESs means acknowledging that not all case studies will yield  
282 the same general conclusions; understanding why; and using this knowledge to build partial  
283 theories with bounded applicability. Middle-range theories, which are contextualized

284 generalizations of phenomena [85], may provide the missing link [86] once clarity is attained  
285 on which theories relate to a particular question or context [49]. Archetype analysis, another  
286 form of mid-range theory, identifies recurrent ‘building-blocks’ and dynamics that explain  
287 outcomes in multiple cases [87] and can help to move beyond analysis of single pairs of  
288 variables.

289         Fourth, consistent use of theories and terminology is vital for comparative research.  
290 Few institutional studies explain how frameworks should be used to collect and store data  
291 (for an example, see [88]). Key ‘necessary developments’ include (1) improving practices for  
292 writing and publishing social-ecological analyses [41], (2) developing incentives to resolve  
293 collective action problems in science, and (3) developing public infrastructure to document  
294 and curate SES knowledge [26,89-91].

295         In summary, institutions are a critical interface between people and ecosystems, and  
296 they play a vital role in regulating and directing social-ecological dynamics. Here we call for  
297 more effectively formalised methods and theory, and a stronger push to connect structure and  
298 process. This research direction can help institutional analysis transcend its current case-  
299 based, ‘list of variables’ approach to achieve much greater levels of generality and a more  
300 rigorous understanding of how to design or foster effective, resilient institutions for  
301 environmental governance and management.

302

### 303 **Acknowledgements**

304 This work was supported by the National Socio-Environmental Synthesis Center (SESYNC)  
305 of the U.S.A., under funding received from the National Science Foundation DBI-1639145.

306

### 307 **References**

- 308 1. Isbell F, Gonzalez A, Loreau M, Cowles J, Diaz S, Hector A, Mace GM, Wardle DA,  
309 O'Connor MI, Duffy JE: **Linking the influence and dependence of people on**  
310 **biodiversity across scales.** *Nature* 2017, **546**:65.
- 311 2. Ostrom E: **Understanding institutional diversity.** Princeton Univ Press, Princeton, NJ.  
312 2005.
- 313 3. Ostrom E: *Governing the Commons: The Evolution of Institutions for Collective Action.*  
314 Cambridge, MA: Cambridge University Press; 1990.
- 315 4. Daw T, Brown K, Rosendo S, Pomeroy R: **Applying the ecosystem services concept to**  
316 **poverty alleviation: the need to disaggregate human well-being.** *Environmental*  
317 *Conservation* 2011, **38**:370-379.
- 318 5. Lubell M: **Governing institutional complexity: The ecology of games framework.**  
319 *Policy Studies Journal* 2013, **41**:537-559.
- 320 6. Coase R: **The new institutional economics.** *The American Economic Review* 1998, **88**:72-  
321 74.
- 322 7. Hall PA, Taylor RC: **Political science and the three new institutionalisms.** *Political*  
323 *studies* 1996, **44**:936-957.
- 324 8. Peters BG: *Institutional theory in political science: The new institutionalism.* Bloomsbury  
325 Publishing USA; 2011.
- 326 9. Rhodes RA, Binder SA, Rockman BA: *The Oxford handbook of political institutions:*  
327 Oxford University Press; 2008.
- 328 10. Frimpong Boamah E: **Polycentricity of urban watershed governance: Towards a**  
329 **methodological approach.** *Urban Studies* 2018, **55**:3525-3544.
- 330 11. Binder C, Hinkel J, Bots P, Pahl-Wostl C: **Comparison of frameworks for analyzing**  
331 **social-ecological systems.** *Ecology and Society* 2013, **18**.

- 332 12. McGinnis MD, Ostrom E: **Social-ecological system framework: initial changes and**  
333 **continuing challenges.** *Ecology and Society* 2014, **19**.
- 334 13. Ostrom E: **A general framework for analyzing sustainability of social-ecological**  
335 **systems.** *Science* 2009, **352**:419-422.
- 336 \*\* Seminal article presenting and summarizing the social-ecological systems framework
- 337 14. Partelow S: **A review of the social-ecological systems framework: applications,**  
338 **methods, modifications, and challenges.** *Ecology and Society* 2018, **23**.
- 339 15. Cox M, Arnold G, Tomás SV: **A Review of Design Principles for Community-based**  
340 **Natural Resource Management.** *Ecology and Society* 2010, **15**:38.
- 341 16. Breitmeier H, Underdal A, Young OR: **The effectiveness of international**  
342 **environmental regimes: Comparing and contrasting findings from quantitative**  
343 **research.** *International Studies Review* 2011, **13**:579-605.
- 344 17. Österblom H, Sumaila UR: **Toothfish crises, actor diversity and the emergence of**  
345 **compliance mechanisms in the Southern Ocean.** *Global Environmental Change*  
346 2011, **21**:972-982.
- 347 18. Song AM, Johnsen JP, Morrison TH: **Reconstructing governability: How fisheries are**  
348 **made governable.** *Fish and Fisheries* 2018, **19**:377-389.
- 349 19. Young OR, Webster D, Cox ME, Raakjær J, Blaxekjær LØ, Einarsson N, Virginia RA,  
350 Acheson J, Bromley D, Cardwell E: **Moving beyond panaceas in fisheries**  
351 **governance.** *Proceedings of the National Academy of Sciences* 2018, **115**:9065-9073.
- 352 20. Goulder LH, Parry IW: **Instrument choice in environmental policy.** *Review of*  
353 *environmental economics and policy* 2008, **2**:152-174.
- 354 21. Lemos MC, Agrawal A: **Environmental governance.** *Annu. Rev. Environ. Resour.* 2006,  
355 **31**:297-325.

- 356 22. Agrawal A: **Sustainable governance of common-pool resources: Context, methods,**  
357 **and politics.** *Annual Review of Anthropology* 2003, **32**:243-262.
- 358 23. Anderies JM, Janssen MA, Ostrom E: **A framework to analyze the robustness of**  
359 **social-ecological systems from an institutional perspective.** *Ecology and Society*  
360 2004, **9**.
- 361 \*This important contribution provides a first step towards operationalising the IAD and SES  
362 frameworks and connecting them to ideas about resilience.
- 363 24. Partelow S, Winkler K: **Interlinking ecosystem services and Ostrom's framework**  
364 **through orientation in sustainability research.** *Ecology and Society* 2016, **21**.
- 365 25. Poteete AR, Janssen M, Ostrom E: *Working together: collective action, the commons,*  
366 *and multiple methods in practice:* Princeton University Press; 2010.
- 367 26. Cox M: **Understanding large social-ecological systems: introducing the SESMAD**  
368 **project.** *International Journal of the Commons* 2014, **8**:265-276.
- 369 27. Hinkel J, Bots PW, Schlüter M: **Enhancing the Ostrom social-ecological system**  
370 **framework through formalization.** *Ecology and Society* 2014, **19**.
- 371 28. Thiel A, Adamseged ME, Baake C: **Evaluating an instrument for institutional**  
372 **crafting: How Ostrom's social-ecological systems framework is applied.**  
373 *Environmental Science & Policy* 2015, **53**:152-164.
- 374 29. Epstein G, Vogt J, Mincey S, Cox M, Fischer B: **Missing ecology: integrating**  
375 **ecological perspectives with the social-ecological system framework.** *International*  
376 *Journal of the Commons* 2013, **7**.
- 377 30. Baggio J, Barnett A, Perez-Ibarra I, Brady U, Ratajczyk E, Rollins N, Rubiños C, Shin H,  
378 Yu D, Aggarwal R: **Explaining success and failure in the commons: the configural**  
379 **nature of Ostrom's institutional design principles.** *International Journal of the*  
380 *Commons* 2016, **10**.

- 381 31. Schoon M: **Governance in transboundary conservation: How institutional structure**  
382 **and path dependence matter.** *Conservation and Society* 2013, **11**:420.
- 383 32. Tekwa EW, Fenichel EP, Levin SA, Pinsky ML: **Path-dependent institutions drive**  
384 **alternative stable states in conservation.** *Proceedings of the National Academy of*  
385 *Sciences* 2019, **116**:689-694.
- 386 33. Morrison TH: **Evolving polycentric governance of the Great Barrier Reef.**  
387 *Proceedings of the National Academy of Sciences* 2017:201620830.
- 388 34. Ribot JC, Agrawal A, Larson AM: **Recentralizing while decentralizing: how national**  
389 **governments reappropriate forest resources.** *World development* 2006, **34**:1864-  
390 1886.
- 391 35. Crona BI, Van Holt T, Petersson M, Daw TM, Buchary E: **Using social–ecological**  
392 **syndromes to understand impacts of international seafood trade on small-scale**  
393 **fisheries.** *Global Environmental Change* 2015, **35**:162-175.
- 394 36. Rocha JC, Peterson G, Bodin Ö, Levin S: **Cascading regime shifts within and across**  
395 **scales.** *Science* 2018, **362**:1379-1383.
- 396 \*\* By exploring interactions between regime shifts, discusses and demonstrates the  
397 complexity of interconnections underlying SES dynamics and sets new goalposts for  
398 the kind of science that we need.
- 399 37. Clement S, Guerrero Gonzalez A, Wyborn C: **Understanding Effectiveness in its**  
400 **Broader Context: Assessing Case Study Methodologies for Evaluating**  
401 **Collaborative Conservation Governance.** *Society & Natural Resources* 2019:1-22.
- 402 38. Ostrom V, Tiebout CM, Warren R: **The organization of government in metropolitan**  
403 **areas: a theoretical inquiry.** *American political science review* 1961, **55**:831-842.
- 404 39. Berardo R, Lubell M: **The ecology of games as a theory of polycentricity: recent**  
405 **advances and future challenges.** *Policy Studies Journal* 2019, **47**:6-26.

- 406 40. Morrison T, Adger WN, Brown K, Lemos MC, Huitema D, Phelps J, Evans L, Cohen P,  
407 Song A, Turner R: **The black box of power in polycentric environmental**  
408 **governance.** *Global Environmental Change* 2019, **57**:101934.
- 409 41. Gerstner K, Moreno-Mateos D, Gurevitch J, Beckmann M, Kambach S, Jones HP,  
410 Seppelt R: **Will your paper be used in a meta-analysis? Make the reach of your**  
411 **research broader and longer lasting.** *Methods in Ecology and Evolution* 2017,  
412 **8**:777-784.
- 413 42. Crumley CL, Levy JE, Ehrenreich RM: **Heterarchy and the analysis of complex**  
414 **societies.** *Archeological Papers of the American Anthropological Association* 1995,  
415 **6**:1-5.
- 416 43. Cumming GS: **Heterarchies: reconciling networks and hierarchies.** *Trends in Ecology*  
417 *and Evolution* 2016.
- 418 \*Describes system structure as being located along axes of lateral and hierarchical controls,  
419 suggesting quantitative measures for institutions.
- 420 44. Chhatre A, Agrawal A: **Trade-offs and synergies between carbon storage and**  
421 **livelihood benefits from forest commons.** *Proceedings of the national Academy of*  
422 *sciences* 2009, **106**:17667-17670.
- 423 45. Gutierrez NL, Hilborn R, Defeo. O: **Leadership, social capital and incentives promote**  
424 **successful fisheries.** *Nature* 2011, **470**:386-389.
- 425 46. Bodin Ö, Robins G, McAllister RR, Guerrero AM, Crona B, Tengö M, Lubell M:  
426 **Theorizing benefits and constraints in collaborative environmental governance:**  
427 **a transdisciplinary social-ecological network approach for empirical**  
428 **investigations.** *Ecology and Society* 2016, **21**.

- 429 47. Lien AM, Schlager E, Lona A: **Using institutional grammar to improve**  
430 **understanding of the form and function of payment for ecosystem services**  
431 **programs.** *Ecosystem services* 2018, **31**:21-31.
- 432 48. Morrison TH, Adger WN, Brown K, Lemos MC, Huitema D, Hughes TP: **Mitigation**  
433 **and adaptation in polycentric systems: Sources of power in the pursuit of**  
434 **collective goals.** *Wiley Interdisciplinary Reviews: Climate Change* 2017, **8**:e479.
- 435 49. Cox M, Villamayor-Tomas S, Epstein G, Evans L, Ban NC, Fleischman F, Nenadovic M,  
436 Garcia-Lopez G: **Synthesizing theories of natural resource management and**  
437 **governance.** *Global Environmental Change* 2016, **39**:45-56.
- 438 50. Poteete A, Janssen M, Ostrom E: **Multiple methods in practice: Collective action and**  
439 **the commons.** Edited by: Princeton University Press; 2009.
- 440 51. Cumming G, Cumming DH, Redman C: **Scale mismatches in social-ecological systems:**  
441 **causes, consequences, and solutions.** *Ecology and society* 2006, **11**.
- 442 52. Epstein G, Pittman J, Alexander SM, Berdej S, Dyck T, Kreitmair U, Raithwell KJ,  
443 Villamayor-Tomas S, Vogt J, Armitage D: **Institutional fit and the sustainability of**  
444 **social–ecological systems.** *Current Opinion in Environmental Sustainability* 2015,  
445 **14**:34-40.
- 446 53. Young OR: *The institutional dimensions of environmental change: fit, interplay, and*  
447 *scale*: MIT press; 2002.
- 448 54. McCord P, Dell'Angelo J, Baldwin E, Evans T: **Polycentric transformation in Kenyan**  
449 **water governance: A dynamic analysis of institutional and social-ecological**  
450 **change.** *Policy Studies Journal* 2017, **45**:633-658.
- 451 55. Aoki M: **Endogenizing institutions and institutional changes.** *Journal of Institutional*  
452 *Economics* 2007, **3**:1-31.

- 453 \* Presents an alternative perspective to the SES framework, focusing on endogenous creation  
454 of institutions.
- 455 56. De Moor M, Berasaín L, Miguel J, Laborda Peman M, van Weeren R, Winchester A:  
456 **Ruling the Commons. Introducing a new methodology for the analysis of**  
457 **historical commons.** *International Journal of the Commons* 2016, **10**:529-588.
- 458 57. Lubell M: **Collaborative partnerships in complex institutional systems.** *Current*  
459 *Opinion in Environmental Sustainability* 2015, **12**:41-47.
- 460 58. McGinnis MD: **An Introduction to IAD and the Language of the Ostrom Workshop:**  
461 **A Simple Guide to a Complex Framework.** *Policy Studies Journal* 2011, **39**:169-  
462 183.
- 463 59. Orach K, Schlüter M, Österblom H: **Tracing a pathway to success: How competing**  
464 **interest groups influenced the 2013 EU Common Fisheries Policy reform.**  
465 *Environmental Science & Policy* 2017, **76**:90-102.
- 466 60. Rissman AR, Gillon S: **Where are ecology and biodiversity in social–ecological**  
467 **systems research? A review of research methods and applied recommendations.**  
468 *Conservation Letters* 2017, **10**:86-93.
- 469 61. Long NE: **The local community as an ecology of games.** *American Journal of Sociology*  
470 1958, **64**:251-261.
- 471 62. Smaldino PE, Lubell M: **Institutions and cooperation in an ecology of games.** *Artificial*  
472 *life* 2014, **20**:207-221.
- 473 63. McGinnis MD: **Networks of adjacent action situations in polycentric governance.**  
474 *Policy Studies Journal* 2011, **39**:51-78.
- 475 64. Villamayor-Tomas S, Grundmann P, Epstein G, Evans T, Kimmich C: **The water-**  
476 **energy-food security nexus through the lenses of the value chain and the**

- 477           **institutional analysis and development frameworks.** *Water Alternatives* 2015,  
478           **8:735-755.**
- 479 65. Sayles J, Garcia MM, Hamilton M, Alexander S, Baggio J, Fischer AP, Ingold K,  
480           Meredith G, Pittman J: **Social-ecological network analysis for sustainability**  
481           **sciences: a systematic review and innovative research agenda for the future.**  
482           *Environmental Research Letters* 2019.
- 483 66. Bodin Ö: **Collaborative environmental governance: Achieving collective action in**  
484           **social-ecological systems.** *Science* 2017, **357**:eaan1114.
- 485 67. Bodin Ö, Alexander SM, Baggio J, Barnes ML, Berardo R, Cumming GS, Dee LE,  
486           Fischer AP, Fischer M, Mancilla Garcia M, et al.: **Improving network approaches**  
487           **to the study of complex social–ecological interdependencies.** *Nature Sustainability*  
488           2019.
- 489 \*Integrates network analysis with the SES framework, laying out a useful conceptual  
490           overview.
- 491 68. Madin JS, Bowers S, Schildhauer MP, Jones MB: **Advancing ecological research with**  
492           **ontologies.** *Trends in ecology & evolution* 2008, **23**:159-168.
- 493 69. Granovetter MJ: **The strength of weak ties.** *The American Journal of Sociology* 1973,  
494           **148**:1360-1380.
- 495 70. Bodin Ö, Tengö M: **Disentangling intangible social–ecological systems.** *Global*  
496           *Environmental Change* 2012, **22**:430-439.
- 497 71. Baggio JA, BurnSilver SB, Arenas A, Magdanz JS, Kofinas GP, De Domenico M:  
498           **Multiplex social ecological network analysis reveals how social changes affect**  
499           **community robustness more than resource depletion.** *Proceedings of the National*  
500           *Academy of Sciences* 2016, **113**:13708-13713.

- 501 72. Agrawal A, Brown DG, Rao G, Riolo R, Robinson DT, Bommarito II M: **Interactions**  
502 **between organizations and networks in common-pool resource governance.**  
503 *Environmental Science & Policy* 2013, **25**:138-146.
- 504 73. Cumming GS: *Spatial Resilience in Social-Ecological Systems*: Springer; 2011.
- 505 74. Bourgeron P, Kliskey A, Alessa L, Loescher H, Krauze K, Virapongse A, Griffith DL:  
506 **Understanding large-scale, complex, human–environmental processes: a**  
507 **framework for social–ecological observatories.** *Frontiers in Ecology and the*  
508 *Environment* 2018, **16**:S52-S66.
- 509 75. Caniglia G, Schöpke N, Lang DJ, Abson DJ, Luederitz C, Wiek A, Laubichler MD,  
510 Gralla F, von Wehrden H: **Experiments and evidence in sustainability science: A**  
511 **typology.** *Journal of Cleaner Production* 2017, **169**:39-47.
- 512 76. Fischer J, Gardner TA, Bennett EM, Balvanera P, Biggs R, Carpenter S, Daw T, Folke C,  
513 Hill R, Hughes TP, et al.: **Advancing sustainability through mainstreaming a**  
514 **social–ecological systems perspective.** *Current Opinion in Environmental*  
515 *Sustainability* 2015, **14**:144-149.
- 516 77. Graham SA: **The Need of Standardized Quantitative Methods in Forest Biology.**  
517 *Ecology* 1929, **10**:245-250.
- 518 78. Cumming GS, Collier J: **Change and identity in complex systems.** *Ecology and Society*  
519 2005, **10**:29 [online] URL: <http://www.ecologyandsociety.org/vol10/iss21/art29/>.
- 520 79. Cumming GS, Barnes G, Perz S, Schmink M, Sieving KE, Southworth J, Binford M, Holt  
521 RD, Stickler C, Van Holt T: **An exploratory framework for the empirical**  
522 **measurement of resilience.** *Ecosystems* 2005, **8**:975-987.
- 523 80. Schluter M, Muller B, Frank K: **The potential of models and modeling for social-**  
524 **ecological systems research: the reference frame ModSES.** *Ecology and Society*  
525 2019, **24**.

- 526 \*Useful integrated analysis of the role and relevance of models for SES research
- 527 81. Baggio JA, Hillis V: **Managing ecological disturbances: Learning and the structure**
- 528 **of social-ecological networks.** *Environmental Modelling & Software* 2018, **109**:32-
- 529 40.
- 530 82. Janssen MA, Baggio JA: **Using agent-based models to compare behavioral theories on**
- 531 **experimental data: Application for irrigation games.** *Journal of Environmental*
- 532 *Psychology* 2016, **46**:106-115.
- 533 83. Magliocca NR, Walls M: **The role of subjective risk perceptions in shaping coastal**
- 534 **development dynamics.** *Computers, Environment and Urban Systems* 2018.
- 535 84. Henrickson L, McKelvey B: **Foundations of “new” social science: Institutional**
- 536 **legitimacy from philosophy, complexity science, postmodernism, and agent-**
- 537 **based modeling.** *Proceedings of the National Academy of Sciences* 2002, **99**:7288-
- 538 7295.
- 539 85. Merton RK: *On sociological theories of the middle range [1949]*: na; 1949.
- 540 86. Meyfroidt P, Chowdhury RR, de Bremond A, Ellis E, Erb K-H, Filatova T, Garrett R,
- 541 Grove JM, Heinimann A, Kuemmerle T: **Middle-range theories of land system**
- 542 **change.** *Global environmental change* 2018, **53**:52-67.
- 543 \*\*Presents important ideas about mid-range theories and bounded applicability, providing a
- 544 role model for institutional analysis.
- 545 87. Oberlack C, Tejada L, Messerli P, Rist S, Giger M: **Sustainable livelihoods in the global**
- 546 **land rush? Archetypes of livelihood vulnerability and sustainability potentials.**
- 547 *Global environmental change* 2016, **41**:153-171.
- 548 88. Gurney GG, Darling ES, Jupiter SD, Mangubhai S, McClanahan TR, Lestari P, Pardede
- 549 S, Campbell SJ, Fox M, Naisilisili W: **Implementing a social-ecological systems**

550 **framework for conservation monitoring: lessons from a multi-country coral reef**  
551 **program.** *Biological Conservation* 2019, **240**:108298.

552 \*Provides an example of how the SES framework can be used to develop monitoring  
553 schemes

554 89. Poteete AR, Ostrom E: **Fifteen years of empirical research on collective action in**  
555 **natural resource management: struggling to build large-N databases based on**  
556 **qualitative research.** *World Development* 2008, **36**:176-195.

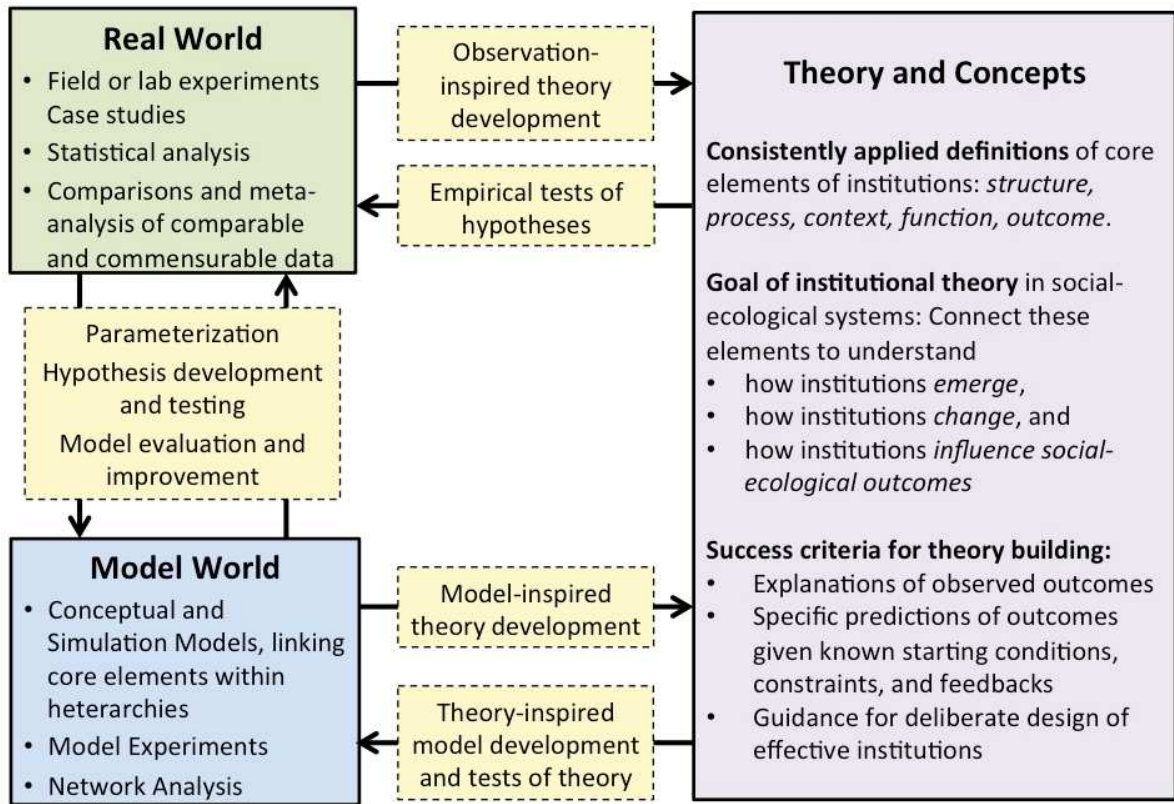
557 90. Young OR, Zürn M: **The international regimes database: Designing and using a**  
558 **sophisticated tool for institutional analysis.** *Global Environmental Politics* 2006,  
559 **6**:121-143.

560 91. Frey UJ, Cox M: **Building a diagnostic ontology of social-ecological systems.**  
561 *International Journal of the Commons* 2015, **9**:595-618.

562

563

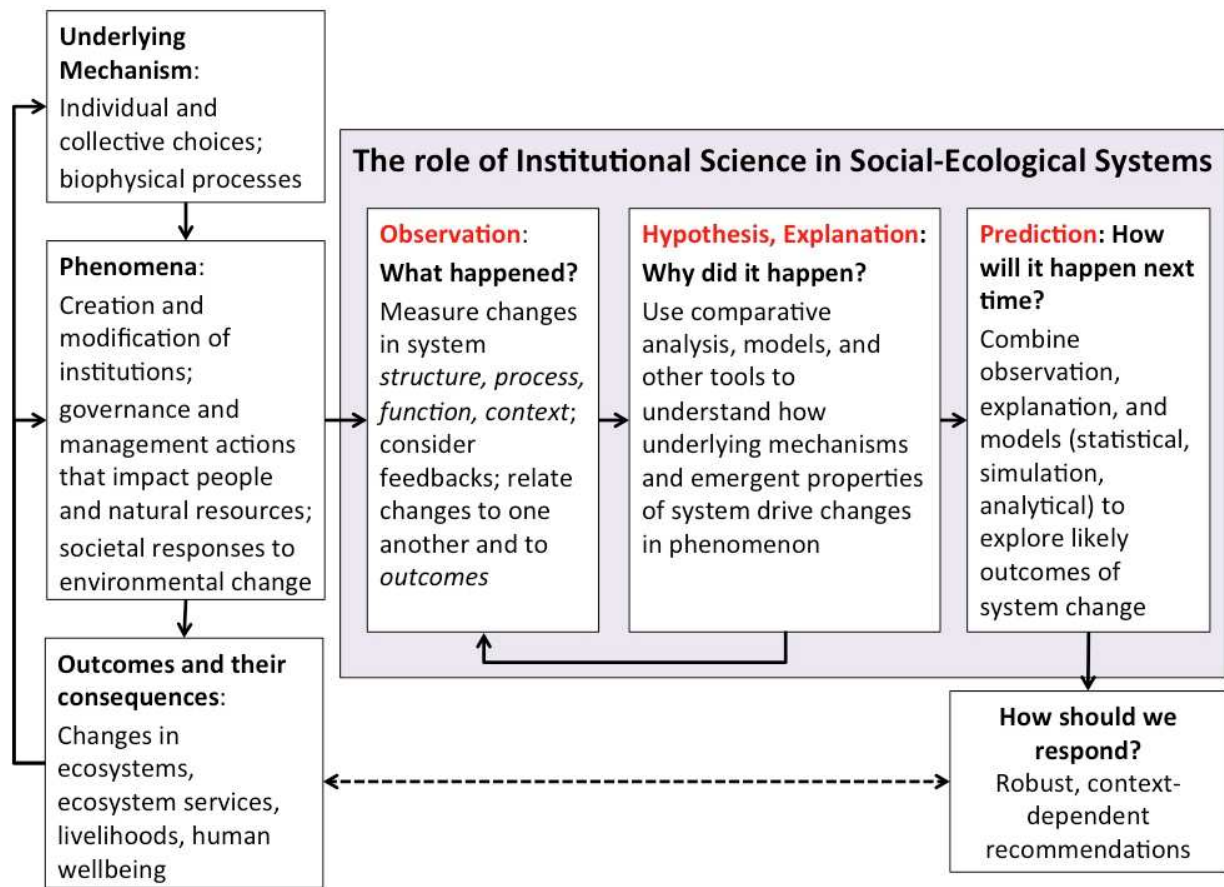
564



566

567 **Fig. 1.** The interaction between theory, models, and empirical data. We propose that the  
 568 primary goal of institutional analysis in environmental and sustainability science is to  
 569 understand how institutions emerge, change, and influence social-ecological outcomes.  
 570 Theory and concepts (including frameworks) should be both inspired and tested through  
 571 observations of real-world phenomena. Models have a critical role to play in the process of  
 572 theory development, acting as a mediator between empirical data and theory as well as an  
 573 approach for generating hypotheses.

574



576

577

578 **Fig. 2.** The role of institutional science in social-ecological systems research. Institutional  
 579 science seeks to understand how underlying mechanisms, both social and ecological, produce  
 580 phenomena relating to the different elements of institutions. These in turn have consequences  
 581 for ecosystems and societies. The scientific process involves observation, explanation, and  
 582 prediction. Once our scientific understanding of the nature of a problem has been improved,  
 583 it can inform responses that lead to desirable outcomes in ecological and social systems.

584

585

### Box 1: Elements of Institutions for Analysis of Social-Ecological Systems

**Institutions** are the laws, rules, norms and customs governing human behavior and human-environment interactions. They often act as intermediaries between people and resources by structuring incentives and property rights that influence resource management decisions. In the study of institutions, identifying general patterns and trends from case studies requires that we describe different institutions in comparable ways and compare equivalent (commensurable) examples. However, broad understandings of institutions and applications of idiosyncratic theories to diverse case studies often render analysis and comparison difficult. To overcome this impasse, we identify five key elements of institutions:

- **Structure**, or system architecture, defines the composition, spatial pattern, and nature of the connections (e.g., power relations, dependencies, and spatial patterns; nestedness) between different components of the study system. Institutions also have their own relational structure ('the grammar of rules') that defines allowable, prohibited, and required uses of natural resources. Analysts often measure institutional structure using networks (nodes and links, i.e. system components and their relationships), or through hierarchical descriptors such as scale. For example, locally specific applications of environmental law may be hierarchically constrained by a principle, such as the right to use navigable waterways for transportation, which is contained in national legislation.
- **Process** refers to interactions (e.g., cooperation, learning, bargaining) that occur over time between and among actors, institutions, and the components of the natural and built environment, resulting in outcomes. For example, democracies often rely on a voting process where voters choose between candidates for leadership roles. Process is influenced or directed by structure, and *vice-versa* (e.g. links between system components emerge through different processes, and the existence of these links can constrain processes). Where processes lead demonstrably and causally to outcomes, they are often described as **mechanisms**. For example, the institutional structure of a commons governance system can be described using the number of different rules in use and their relationships to one another (e.g., rules about livestock access to water may be subordinate to rules relating explicitly to human drinking water). Structural change can be described as the difference in these rules and relationships between two points in time. Understanding why institutional change has occurred depends on understanding the processes that underlie it, such as the ways in which rules can be changed. Such processes will interact with, and often depend upon, the existing structure.
- **Function** describes the role or objective of an institution in relation to broader system dynamics or societal goals. For example, rules that limit over-grazing and over-fishing function to prevent a tragedy of the commons situation. Functions may be purposive (i.e., the system has been designed to achieve a given function), unintentional, or subverted. Subversion occurs when a rule that has been introduced for one purpose is co-opted to support another purpose. For example, Article VIII of the International Convention for the Regulation of Whaling allows countries to undertake whaling for scientific research. This loophole continues to be exploited by Japan to harvest whales without a genuine scientific justification (Clapham, 2017).
- **Context** describes the dynamic environment that is considered exogenous or fixed within the study system for the purposes of analysis. Context has spatial and temporal dimensions and includes both biophysical and social components, such as geography, land use history, or power relations.
- **Outcomes** describe the impact or difference that institutions and institutional processes make to the social and ecological context. For example, in Madagascar, the radiated tortoise *Astrochelys radiata* was historically abundant because the Mahafaly and the Antandroy people had a taboo against eating it. Movement of people from other groups into the tortoise's range has resulted in the taboo being abolished leading to widespread radiated tortoise consumption and IUCN Red-Listing of the tortoise as critically endangered (Lingard et al., 2003).