Sustainability Science • Sustainability Science: A guide for researchers

An Integrative Framework for Sustainability Science

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Sustainability science draws from a great variety of perspectives including tacit (traditional and practical) knowledge, ecology and economics, engineering and medicine, political science and law, and a multitude of others. These multiple perspectives are generally a source of strength, bringing potentially complementary bodies of theory, data, and methods to bear on the challenges of sustainable development. But they also have meant that the field remains somewhat fractured into distinct schools of thought, research programs, and other “island empires,” each characterized by its own idiosyncratic origins, terminologies, publication venues, case studies, and conceptual frameworks. While many individual disciplines have contributed something to sustainability research, interdisciplinary research programs have been the most significant shapers of the part of that research that is our target in this Research Guide. We list the programs that we judge to have been most influential in Table 1.¹ The good news is that these research programs are increasingly melding, sharing scholars and ideas and generating exciting hybrid research efforts. The bad news is that the integration remains incomplete, with the result that sustainability science today remains substantially less than the sum of its impressive parts. Integrating research across the island empires of the field would almost certainly help to realize its potential for informing agitation in support of sustainable development.

We offer here as one step toward promoting that integration a new Framework for Research in Sustainability Science. **Frameworks**² are usefully thought of as the most general form of conceptualization in science ([Ostrom 2011](#)). They provide checklists or building blocks of **elements and relationships**³ for consideration in constructing theories or models that seek to explain particular patterns or phenomena. The framework we present here simply highlights the “union set” of elements and relationships introduced by the research programs listed in Table 1. We emphasize that this framework is not intended as a master plan for some grand theory of the field. Rather, we offer it as our admittedly subjective synthesis of the building blocks that past research has shown to be particularly useful across a wide range of contexts and that should therefore be given serious consideration in ongoing efforts to construct and test middle-range theories about how to promote sustainable development ([Meyfroidt et al. 2018](#)). We believe that adoption of a common framework of elements and relationships such as that proposed here would help to integrate the various pieces of sustainability science, to facilitate interaction across the field, and thus to accelerate progress in the pursuit of sustainability. The remainder of this chapter characterizes the principal elements and relationships that our review suggests should be included in the checklists captured by an integrative

framework for sustainability science. Subsequent chapters explore how these concepts have been used to inform agitation for sustainable development.

Table 1: Research programs that have shaped sustainability science

Name(s)	Special contribution(s)	Recent reviews(s)
Complex adaptive systems (CAS)	Local action by heterogeneous (diverse) agents, constrained by higher level structures, central role of innovation/novelty	(Levin et al. 2012 ; (Preiser et al. 2018))
Coupled human and natural systems (CHANS)	Reciprocal links between human and natural systems; special attention to links across space	(Hull and Liu 2018)
Coupled human-environment systems (CHES)	Place-based analysis of linkages, emphasizing physical and biotic environment; actors and agency	(Moran 2010)
Earth system governance (ESG)	Highlights importance of institutional design, agency, and power for governing nature–society interactions; emphasis on transitions and inequality	(Burch et al. 2019)
Ecosystem services / natural capital	Goods and services flowing from functioning ecosystems; role of institutions and technologies in shaping production of and human access to those services	(Peterson et al. 2018 ; Bennett 2017)
Environmental justice (EJ)	Focus on inequality and environmental harm, highlights vulnerability of poor and marginalized communities to pollution, maldistributions of power	(Agyeman et al. 2016 ; Menton et al. 2020)

Industrial ecology/ social metabolism /circular economy	Focus on use of energy and biophysical resources; special attention to flows in and out of manufactured structures; technology design; trade; adequacy of sources and sinks	(Haberl et al. 2019 ; Loste, Roldán, and Giner 2019 ; Zimmerman et al. 2020)
IPBES conceptual framework (Intergovernmental Platform on Biodiversity and Ecosystem Services)	Focus on biodiversity benefits for people, collaborative processes for fair mobilization of multiple value, multiple knowledge systems	(Díaz et al. 2018).
Livelihoods	Local actors' entitlements and capabilities to secure access to resources and their benefits; role of agency, power, politics, and institutions	(Scoones 2009).
Pathways to sustainability	Normative emphasis on poverty alleviation, local knowledge and social justice as defined by and for particular people and contexts; analytic emphasis on power, politics, roles of problem framing, and narratives	(Leach, Scoones and Stirling 2010).
Resilience thinking	Intertwined social/ecological systems as CAS displaying multiple regimes; tipping points; fast versus slow variables; coping with risk, adaptive capacity	(Reyers et al. 2018).
Social-environmental systems	Co-production of useful knowledge by actors and analysts; boundary work; trust; power; monitoring, feedback for adaptive management	(Turner II et al. 2016).
Socio-ecological systems (SES)	Action situation focus on how actors use resources in particular contexts, role of actors and institutions in governance outcomes, and multi-level (cross-scale) linkages	(McGinnis and Ostrom 2014).

Socio-technical transitions / multi-level perspective (MLP) / strategic niche management (SNM)	Technology change and innovation as multi-level, evolutionary processes; transitions among sociotechnical regimes as whole-system, deep-structure, long-term, path-dependent, incumbent actors and institutions	(Loorbach, Frantzeskaki, and Avelino 2017 ; Markard, Geels, Raven 2020)
Sustainable consumption-production (SCP)	Beyond control of pollution from production alone or consumption lifestyles alone to joint consideration of coupled consumption and production activities	((Geels et al. 2015); Schröder et al. 2019)
Welfare, wealth, and capital assets	Well-being across generations linked to wealth defined by access to resource stocks from nature and society; substitutability among stocks	(Irwin, Gopalakrishnan, and Randall 2016 ; (P. S. Dasgupta 2018))

1 Findings: Key elements and relationships of the Anthropocene as a Complex Adaptive System

In this section, we first describe the elements and relationships that have been found to be important for sustainability science research. We organize our discussion here into four parts: nature–society interactions, governance, complexity, and context dependence. In Section 2 we integrate this description in a Framework for Research in Sustainability Science (see Figure 1, in Section 2).

Environment and development: The “inseparable” connections between environment and development that were noted by the Brundtland Commission constitute the foundation of the Framework. Research has highlighted three aspects of those connections that are central to sustainable development. We summarize them here and address them in more detail throughout the Research Guide.

Nature–society interactions⁴: Recent research in sustainability science has shown how thoroughly the elements of nature and society are intertwined in deeply coevolutionary relationships that shape dynamical **pathways of development**⁵ ([Reyers et al. 2018](#)). An immediate consequence of these findings is that talk of environmental-sustainability, or social-sustainability or other forms of “hyphenated-sustainability,” is fundamentally misleading and at odds with the integrating aspirations of sustainability science. A research-informed use of the term “sustainable” should therefore always—

and only—refer to the integrated pathways of development resulting from nature–society interactions in the Anthropocene System.

Goals: Sustainability science is a problem-driven field. The ongoing normative debates on the goals of sustainable development—what they are, have been, and should be—therefore occupies a core position in the Framework. The most important constituents of sustainability goals vary across groups, places, and times. But a widely shared common vision has begun to emerge focused on the fair or equitable advancement of human well-being within and across generations ([Stiglitz, Fitoussi, and Durand 2019](#)). The Sustainable Development Goals (SDGs) recently articulated under the auspices of the United Nations have reaffirmed this overarching goal ([United Nations 2015](#)). They have also, however, somewhat muddled the waters by failing to distinguish between the ends or ultimate goals of sustainable development (promoting well-being) and the multiple means of achieving those goals ([P. S. Dasgupta 2018](#)).

Resources have always been a central focus of research on sustainability. Today, the resource concept has broadened from early work on forests and fisheries to include multiple stocks of capital assets from which people draw goods and services in efforts to achieve their goals. Some resource stocks considered in contemporary sustainability science are usefully thought of as “natural” in that they come principally from nature ([Barbier 2019](#)), e.g., biodiversity, ecosystems, the physical environment (e.g., climate), and minerals. Others are “anthropogenic,” or made by people ([Díaz et al. 2015](#)) e.g., manufactured capital, human capital, social capital, and knowledge capital. Development pathways in the Anthropocene System can conserve, deplete or build all of these foundational resource stocks. But one of the most important findings of sustainability science has been that natural *and* anthropogenic resources, together with the dynamic relationships among them, should be treated as the joint foundations on which well-being can be built.

Governance: A second part of the Framework brings to bear on the core concepts questions of **governance**⁶: the arrangements by which “any collectivity, from the local to the global, seeks to manage its common affairs”

([Ruggie 2014, 5](#)). The importance and variety of governance arrangements bearing on sustainability were given enormous impetus through the work on resource commons by Elinor Ostrom and her colleagues ([McGinnis and Ostrom 2014](#)). The elements and relationships bearing on governance that have received most attention in research on sustainable development include actors, institutions, and, more recently, power. We summarize how these ideas have been used in the scholarly literature immediately below and expand on them later in this Research Guide.

Actors⁷ in the Anthropocene System come from both the natural and social subsystems. The former has been construed to include some non-human organisms and their assemblages; the latter to include

people, communities, firms and other organizations, states, and comparable entities. What actors have in common is agency: the ability to choose or decide. Actors have not only the ability to directly consume or produce resources but also (for social actors) the ability to articulate goals, construct narratives, and influence which institutional structures are in play ([Betsill, Benney, and Gerlak 2020](#)). Characteristics of social actors that have proven salient for sustainability science include their values, beliefs, empathy, interests, capabilities for learning and innovation, and power.

Institutions⁸ are the structural dimension of governance. They constitute the rules, norms, rights, culture, and widely shared beliefs that help to shape the behavior of social actors in their relationships with one another and with nature ([Ostrom 2005](#)). Institutions are created, reinforced, and changed by actors. Much of the analytic work in sustainability science seeks to evaluate how specified changes in institutions—say, the imposition of a carbon tax ([Stiglitz 2019](#))—have affected or are likely to affect the prospects for achieving sustainability goals.

Power⁹ is the ability of actors to affect the beliefs or actions of other actors ([Hicks et al. 2016](#)). can both constrain and enable what people think and do ([Gerlak et al. 2019](#)). Power mediates the relationships among actors, institutions, resources, and goals. Actors can either work within inherited power structures or attempt to change those structures. Actors with more power can more easily change or maintain existing structures to further their power.

Complexity: This third part of the Sustainability Science Framework seeks to capture the fundamentally important finding that the Anthropocene System is a **complex adaptive system (CAS)**¹⁰ ([Preiser et al. 2018](#)). Three fundamental attributes of the Anthropocene make it a complex adaptive system: the persistent **heterogeneity**¹¹ (individuality, diversity) of its elements; relationships (interactions) among those heterogeneous elements that are local or context specific; and autonomous selection processes that enhance some elements (but not others) based on the outcome of the local interactions ([Levin 2002](#)). These attributes underlie several emergent properties of the Anthropocene that have turned out to be of fundamental importance for understanding the prospects for sustainable development, among them: hierarchical organization; novelty and innovation; horizontal connections; vertical connections; and far-from-equilibrium dynamics. In what follows we discuss each of these emergent properties and their implications for sustainable development, drawing heavily on the foundational framing of Levin, Arrow, and their coauthors ([Arrow, Ehrlich, and Levin 2014](#)).

Hierarchical organization is an emergent property of the fundamental attributes of the Anthropocene System noted above. Many levels may be in play for any particular case. Three, however, are most commonly referred to in sustainability research: a meso- or focal-level defined by the particular phenomenon of interest (e.g., a community); its neighboring macro-level, consisting of

relatively persistent patterns of elements and relationships that constrain dynamics at the focal level (e.g., geography, climate zones); and its neighboring micro-level, at which heterogeneous local interactions take place that may ultimately influence focal-level dynamics (e.g., novel traits or inventions).

Novelty and innovation: From the perspective of sustainability science, the most important and most overlooked implication of the complex adaptive character of the Anthropocene is its continuous generation of novelty and innovation. This can take biological, technological, or institutional forms. It usually arises at the micro-level through the fundamental attributes noted above but can bubble up to the meso-level when suitable vertical selection mechanisms are in play. There, especially when macro-level boundary conditions are suitably aligned, novelty and innovation drive development pathways to evolve in fundamentally unpredictable ways ([Arthur 2015](#))([Hagstrom and Levin 2017](#)). These important themes have long been explored in the context of evolutionary biology and economics but have only begun to enter sustainability scholarship, largely through the literatures on transformations and transitions ([Geels 2020](#)). The implications for sustainability of treating novelty seriously are profound and further explored in the [Chapter on Capacity to Transform](#).

Horizontal connections among individual actors and other elements of the Anthropocene System exist at all hierarchical levels. But they are generally incomplete, i.e., the heterogeneity of the system persists rather than becoming homogenized. Research therefore has to take seriously the persistent heterogeneity of different patches of the system and the partial connections among them. Sustainability science has long focused attention on the externality aspect of these connections ([P. S. Dasgupta and Ehrlich 2013](#)). Studies of horizontal connections have also addressed the propagation of disturbance and novelty through the Anthropocene System ([May, Levin, and Sugihara 2008](#); [Rogge, Kern, and Howlett 2017](#); [Gilarranz et al. 2017](#)). More generally, studies of both teleconnections among people, materials, information, and places ([Hull and Liu 2018](#)) and of social connections in actor networks ([Sayles et al. 2019](#)) are generating sufficiently useful insights to suggest that horizontal connections should be considered in most new studies for sustainability science.

Vertical connections¹² link hierarchical levels of the Anthropocene in a variety of important ways. Sustainability science scholarship has long studied connections reaching down from the macro-level to influence meso-(focal) level dynamics: e.g., work on driving forces ([Dietz 2017](#)); path-dependencies ([Seto et al. 2016](#)); and other slow variable processes such as climate change and globalization ([Biggs et al. 2015](#); [Tu, Suweis, and D'Oodorico 2019](#)). The profound implications of upward connections from the micro- to meso-scale have already been noted in the discussion of innovation above. More recently, research has begun to emphasize the importance of two way flows connecting multiple hierarchical levels ([Martín-López et al. 2019](#)). Increasing attention is also being given to the role of **polycentric**¹³

connections across levels and elements of governance in guiding action for sustainability ([Oberlack et al. 2018](#)).

Far-from-equilibrium dynamics are the norm, not the exception in the complex adaptive system of the Anthropocene. These dynamics exhibit multiple **regimes**¹⁴, or characteristic sets of behaviors driven by a particular set of dominant relationships, feedbacks, or rules of the game.¹⁵ Characteristic of regimes is that within them, small perturbations—whether caused by chance, internal dynamics or outside disturbances—encounter feedbacks that tend to push the system back toward its earlier state or to lock in its development pathway. Separating neighboring regimes are **thresholds**¹⁶ (also called “tipping points”). For a regime operating near such a threshold, especially when internal feedbacks are weak, small disturbances can shift the system into a neighboring regime and thus down a different pathway of development ([Biggs, Peterson, and Rocha 2018](#); [Fuenfschilling and Binz 2018](#); [Otto et al. 2020](#)).¹⁷ The situation is further complicated by the fact that both the configuration of neighboring regimes and the boundaries separating them may be altered by a variety of factors ([Scheffer 2009](#)). Finally, since multiple regimes exist in the Anthropocene System, multiple opportunities exist for interactions or interplay among them ([Young 2011](#)) and for cascading regime shifts within and across hierarchical levels ([Rocha et al. 2018](#); [Steffen et al. 2018](#)). One of the most exciting additions to sustainability science over the last decade has come from a vibrant community of researchers that originally studied historical regime transitions in socio-technical systems, but that is now contributing directly to understanding transitions toward sustainability ([Loorbach, Frantzeskaki, and Avelino 2017](#)). We review this work in the [Chapter on Capacity to Transform](#).

Context dependence: The fourth major component of the Framework addresses the ubiquitous finding of research on sustainable development that context matters. The development pathways generated by complex nature–society interactions are almost always dependent on conditions characterizing the case at hand, including the particular configurations of nature and society; of actors, institutions, and power; and of the particular historical legacies that are in play ([Agrawal 2003](#); [Bebbington et al. 2018](#)). This is why scholars, as noted earlier, have tended to avoid grand unifying theories of sustainability. Instead, they have focused on case studies or, more ambitiously, on constructing and testing middle range theories that transcend individual cases but still confine themselves to particular contexts ([Meyfroidt et al. 2018](#)).

Action situations¹⁸: Successful integration of research results across cases requires systematic approaches to selecting and characterizing context. Various disciplines have developed multiple research methodologies to help in this important task. In general, these all admonish researchers and analysts to “bound the problem” by explicitly identifying which temporal and spatial scales, elements, and relationships are explicitly treated “inside” a particular study, and which are provisionally set “outside” or otherwise excluded. One of the most fully articulated approaches to contextualization in

sustainability studies focuses on the concept of an action situation. This was initially formulated in Ostrom's Institutional Analysis and Development (IAD) framework as an approach to characterize contexts of social interactions through which people and organizations make choices about using resources to achieve their goals ([McGinnis and Ostrom 2014](#)). It has since been extended to contextualize the use of resources not only in terms of interactions within society but also including the interactions between society and nature and among multiple elements of the environmental system ([Schlüter et al. 2019](#)). It is in this broader sense that we use the term “action situation” when addressing the importance of contextualizing sustainability science.

Careful attention to specifying action situations (by whatever name) has helped scholars working on problems relevant to sustainability to make progress in crafting middle-range theories that take context seriously but rise above the level of individual case studies. Notable examples include research on resource commons ([Boyd et al. 2018](#)), poverty traps ([Barbier and Hochard 2019](#)), land use change ([Meyfroidt et al. 2018](#)), energy transitions ([Chen et al. 2019](#)), and urbanization ([Seto et al. 2017](#)). Most such mid-range work about the Anthropocene is potentially relevant to the pursuit of sustainability. But only a subset of it has explicitly addressed the central concerns of sustainability science: advancing goals of inclusive well-being through the stewardship of natural and anthropogenic resources. Most of that subset has in common its use of a consumption-production perspective (see below).

Consumption-production relationships: The subset of middle-range theorizing that has contributed most to the pursuit of sustainability addresses action situations that explicitly link aspects of well-being (e.g., health) to the consumption of the goods and services (e.g., food) that flow from production activities (e.g., farming) and that draw on, and reinvest in, the underlying resource base (e.g., land, labor, etc.). The literature that has focused most consistently on such action situations contextualizes the complex, multilevel character of nature–society interactions in terms of sustainable consumption-production systems ([Wang et al. 2019](#)). Sustainable consumption and production have also emerged as the single most widely shared component of the UN's SDGs ([Le Blanc 2015](#)). Much of the relevant research still focusses on parts of the system, with consumption studies emphasizing the role of actors' values, incentives, and practices ([Bengtsson et al. 2018](#)) and production studies emphasizing efficient and even circular use of resources (e.g. [Merli, Preziosi, and Acampora 2018](#)). Increasingly and encouragingly, however, scholars are exploring action situations for sustainable development in terms of truly integrated systems of consumption and production ([Geels et al. 2015](#)).

We are convinced that adopting a consumption-production perspective for defining action situations in sustainability science research would be useful for three reasons. First, it could serve as a general integrative concept for the exciting work on specific middle-range theories that have usefully contextualized our understanding of important classes of nature–society interactions. Second, it could

prod other middle range theories of nature–society interactions to connect better with sustainability science by explicitly linking goals through consumption and production processes to underlying resources. Finally, it could serve as a reminder that the action situations addressed by those various middle-range theories seldom exist in isolation from one another. Rather, multiple consumption–production systems are generally in play, drawing on the same resources for different purposes and thereby affecting the challenges and opportunities facing one another ([Schlüter et al. 2019](#)). The resulting nexus of interacting action situations has proven extremely difficult to untangle ([Galatsi, Veysey, and Huber-Lee 2018](#)) and stands as a frontier challenge for efforts to integrate research on sustainability ([Liu et al. 2018](#)).

2 Integration: A Framework for Research in Sustainability Science

This chapter has outlined the union set of elements and relationships identified by existing research programs that have proven sufficiently useful to merit consideration in future research on sustainable development. It's admittedly a long and potentially confusing check list. We therefore provide in Figure 1 a visual summary. We emphasize that the figure is a framework, not a theory or model. That is, we intend it as a checklist of terms and concepts, each of which has a record of sometimes being helpful in understanding sustainable development depending on the context of interest. Whether particular entries in the framework provide significant explanatory power in particular cases, and whether additional elements and relationships are needed to explain those cases, can only be determined by doing the relevant empirical research for a given action situation. But sustainability science has, perhaps, advanced to the point that future research should not casually ignore any of the elements and relationships highlighted in the Framework summarized in Figure 1.

Figure 1 A Framework for Research in Sustainability Science.

Figure 1 A Framework for Research in Sustainability Science. The framework summarizes a checklist of elements (variables) and relationships (processes) that experience suggests are worth considering in sustainability science research. These are described at length in the text and summarized here.

At the core of much research on sustainability are the intertwined nature–society interactions depicted in the center of the figure. Sustainability science research has focused on the four key elements involved in those interactions that are depicted in the ovals of the figure: *goals* (what people want from sustainable development), *resources* (the capital assets of the Anthropocene System, which may be natural or anthropogenic), *actors* (communities, firms, states and other entities with agency that strive to use resources to achieve their goals), *institutions* (rules, norms, culture, beliefs that shape the behavior of actors). These key elements (ovals) are bound together through key relationships of *consumption and production*, mediated by the relative *power* of different actor groups to affect one another’s actions and beliefs.

Context dependence is a central finding of sustainability research: Multiple sets of nature–society interactions are always in play (e.g., multiple countries, multiple sectors), each characterized by its own particular variants of the key elements and relationships noted above. The importance for researchers of specifying context for the particular nature–society interactions (action-situations) they are studying, while keeping in mind the simultaneous existence of other potentially relevant action situations, is suggested by the multiple sets of nature–society interactions depicted in the background at

the center of the figure and the potential for *horizontal connections* among them (e.g., transboundary pollution, spill-over of local discoveries, migration, trade).

Nature–society interactions constitute a complex adaptive system. This results in an emergent hierarchical structure, pictured here in terms of *meso*-, *macro*-, and *micro*-levels of organization. Lower levels in the hierarchy highlight the *heterogeneity* (diversity) of elements that are often treated as aggregates at higher levels. The hierarchical, heterogeneous character of the overall system is another reason why *connections* have become such a focus of sustainability research: the horizontal connections within levels noted above, but also vertical connections between micro- and meso-levels (e.g., innovation), and between meso- and macro-levels (e.g., climate change). The *pathways of development* that emerge from all the elements and relationships noted here are strongly path dependent, exhibiting multiple *regimes* (valleys guiding the development pathways in the figure) separated by *thresholds* or *tipping points* (ridges and cliffs in the figure). *Adaptation* keeps development pathways within their original regimes in the face of shocks. More rarely, *transformation* of a development pathway from one regime into another can occur due to changes in the underlying “landscape” created by nature–society interactions, or due to the emergence of new technologies or social movements that challenge existing path dependence (“cross-overs” in the pathways shown in the figure). Would-be transformational changes can falter; however, if they fail to cross into a new stable regime but end up clinging to an unstable trajectory that eventually becomes untenable and precipitates development back into its original regime (see the trajectory running through the “green meadow” in the figure’s future pathway).

Footnotes

1. The method we used to identify the research programs listed in Table 1 is described in the Supplemental Materials. The Supplemental Materials also include a bibliometric analysis of these research programs we hope interested readers will find useful. (Follow the Supplemental Materials menu in the online version of this collection or link at <https://www.sustainabilityscience.org/pub/kzs257kc>.) ↵
2. **Frameworks:** the most general form of conceptualization in science; provide checklists or building blocks for consideration in constructing theories or models (Ostrom 2011) ↵
3. **Elements:** variables or components of structure; may be coupled via functional relationships or processes ↵
4. We prefer this framing of the interactions that shape the Anthropocene over alternative framings that, however broad their intended meaning today, reflect in their terminology various disciplinary path-dependencies that some perceive as narrowing what ought to be an inclusive vocabulary. In particular, we invite readers to join us in seeing “nature–society” interactions in the broadest possible sense, along the lines suggested by common usage of “natural” and “social” sciences. We see this as broader than “human–environmental” interactions (which connote to many a diminution of the importance of how people organize their relationships with one another), “social–ecological” interactions (which connote to many a diminution of the physical aspects of nature such as climate)

and “socio-technical” interactions (which connote to many a diminution of the importance of nature in the Anthropocene System). [↵](#)

5. **Pathways of development:** temporal changes in patterns of observed or predicted covariation in nature and society [↵](#)

6. **Governance:** the arrangements by which any collectivity, from the local to the global, seeks to manage its common affairs (Ruggie 2014) [↵](#)

7. **Actors:** entities with agency—the ability to choose or decide; they include people, communities, firms, other organizations, and states, but also some nonhuman organisms and their assemblages (see also our definition for **power**) [↵](#)

8. **Institutions:** the rules, norms, rights, culture, and widely shared beliefs that shape the behavior of social actors in their relationships with one another and with nature [↵](#)

9. **Power:** the ability of actors to deploy their agency in ways that affect the beliefs or actions of other actors [↵](#)

10. **Complex adaptive systems (CAS):** relationships among diverse elements that give rise to novelty and dynamics that feed back on those elements and relationships, resulting in a continually evolving system [↵](#)

11. **Heterogeneity:** characteristics of actors and other elements that are distinctive and cannot be understood in terms of averages (also referred to as individuality or diversity) [↵](#)

12. We use the term “vertical” connections to characterize linkages across levels. The more conventional “cross-scale” terminology is ambiguous in that it can be read to refer to both spatial and temporal domains. [↵](#)

13. **Polycentric:** systems with multiple sources of partial authority and semiautonomous decision-making that interact to create multi-level governance arrangements [↵](#)

14. **Regimes:** sets of dominant relationships (both natural and social) that give rise to characteristic dynamics and development pathways [↵](#)

15. The concept of *regime* has been used to characterize natural systems (e.g., river flow regimes, prey-predator regimes), social systems (e.g., the world trade regime, the nuclear nonproliferation regime), and Anthropocene Systems characterized by nature–society interactions (e.g., the climate regime, the world food regime). For sustainability science, this last, more inclusive sense seems most appropriate and is therefore what we mean when using the term throughout this review. [↵](#)

16. **Threshold:** condition at which small changes can have big effects, leading to qualitatively different pathways of development; closely related to tipping point and catastrophic bifurcation [↵](#)

17. We follow Scheffer (Scheffer 2009, 83) in using the term “regime shift” to refer to the general phenomenon of a rapid change from one set of dynamics to another, and reserve the term “critical transition” for the subset of regime shifts that is due not to changes in external conditions but rather due to a change in dominant feedbacks. See Milkoreit et al. (2018) for a review of how these terms are used in the literature. [↵](#)

18. **Action situations:** contexts of nature–society interactions in which particular actors, operating in particular institutional structures, make choices about using particular resources to achieve their particular goals [↵](#)

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