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Sustainability Science: Toward a Synthesis

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Abstract

This review synthesizes diverse approaches that researchers have brought to bear on the challenge of sustainable development. We construct an integrated framework highlighting the union set of elements and relationships that those approaches have shown to be useful in explaining nature–society interactions in multiple contexts. Compelling evidence has accumulated that those interactions should be viewed as a globally interconnected, complex adaptive system in which heterogeneity, nonlinearity, and innovation play formative roles. The long-term evolution of that system cannot be predicted but can be understood and partially guided through dynamic interventions. Research has identified six capacities necessary to support such interventions in guiding development pathways toward sustainability. These are capacities to (*a*) measure sustainable development, (*b*) promote equity, (*c*) adapt to shocks and surprises, (*d*) transform the system into more sustainable development pathways, (*e*) link knowledge with action, and (*f*) devise governance arrangements that allow people to work together in exercising the other capacities.

Contents

1. SCOPE OF THE REVIEW

We present here a strategic perspective on the central findings and current challenges of sustainability science. Research on sustainable development has grown explosively since the mid-1980s, with the field of sustainability science emerging as a global collaboration network in the early years of this century (1). Other reviews, many of which we cite here, have assessed in detail the research on particular parts of the field. Our goal is to complement those focused assessments with a synthesis that highlights the principle insights that have emerged from sustainability science and their practical implications for the pursuit of the goals of sustainable development. We aim to provide a manageable overview of the field for scholars seeking to locate their work within the broad enterprise of sustainability science or to catch up on important findings in parts that are not their own, or to forge new collaborations across distant parts of this rapidly expanding and evolving enterprise.

1.1. Sustainable Development

Sustainability science, like agricultural science or health science, is an applied science defined by the practical problems it addresses—specifically, the problem of sustainable development (2). That problem was defined a generation ago by the World Commission on Environment and Development (the Brundtland Commission) in a prescient statement that merits careful rereading today:

> "Environment" is where we all live; and "development" is what we all do in attempting to improve our lot within that abode. The two are inseparable. . . . Humanity has the ability to make development sustainable: to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. (3, pp. ix, 8)

Well-being: an integrating concept of the good life, the constituents of which will vary among people and across time

Capacity: the intention and the ability to accomplish a task or achieve an outcome

Anthropocene System: a term for what some call the earth system or world system that better captures the increasingly global and intimate intertwining of nature and society

Subsequent deliberations in all manner of public forums—from community gatherings to the United Nations (UN) General Assembly—have reaffirmed the Commission's vision but also expanded it. The challenges of sustainable development today are generally seen in terms that go beyond just meeting basic human needs to embrace a broader vision of sustainability as fairness: enhancing human well-being to more equitably meet the needs of both current and future generations (4). Efforts to promote sustainability also increasingly acknowledge that its pursuit should treat humans, in Amartya Sen's phrase (5, p. 7), "not as patients whose interests have to be looked after, but as agents who can do effective things"—who have the freedom and capacity to participate in setting their own sustainability goals and in choosing how to pursue them.

The growing concern for making development sustainable has been a response to tensions implicit in two global trends: rapidly increasing human well-being and rapidly increasing environmental degradation. These two trends, taken together, have come to be the perplexing and alarming characterization of what many are now calling the Anthropocene System (6). The first global trend, depicted by Angus Deaton as "the great escape" (7), consists of the unprecedented improvements in human health, knowledge, and material well-being that began in the late nineteenth century and accelerated especially in the second half of the twentieth century. By the early twenty-first century more than 80% of the people on Earth had life expectancies higher than those of people in the richest parts of the world as recently as 1950. And the fraction of the world's population living in absolute poverty was lower than it had ever been. This great escape had clearly left some people and regions behind, resulting in substantial inequalities (8). By almost any metric, however, human well-being on Earth had never been higher, at least before the outbreak of the SARS-CoV-2 pandemic (9). The second Anthropocene trend, described by John McNeill as "the great acceleration," consists of the increasing magnitude and global extent of human impacts on nature (10). By the dawn of the twenty-first century, no corner of the Earth's environment had escaped transformation by human activities. The great acceleration had certainly entailed significant cases of environmental protection and restoration. But its overall thrust showed few signs of abating, as reflected by increasing attention to the planet's great poisoning by toxic chemicals (11), the mass extinction of its biota (12), and above all its multifaceted climate crises (13).

The Brundtland Commission warned that what it saw as the present trends of what we now call the Anthropocene System could not be sustained. It also expressed a guarded hope that humanity could still achieve a common future of sustainable development. But how?

1.2. Sustainability Science

Today's development pathways are tightly bound up with dominant arrangements of states, markets, firms, and other powerful incumbent interests. Too many of these seem so dedicated to their

own self-preservation that they appear unwilling to heed the ubiquitous distress signals of today's Anthropocene. Indeed, many of these interests seek to block the innovations and rearrangements that are needed to address the crisis of unsustainability. Breaking such blockages so as to enable the serious pursuit of sustainability will almost certainly require a radical restructuring of the politics of the Anthropocene (14). The role of science in that restructuring has been captured by Amartya Sen in his call for informed agitation (5)—agitation because political mobilization is necessary to tackle the powerful entrenched interests behind a business-as-usual attitude that disproportionately benefits a few people in their here and now at the cost of impoverishing the prospects of the many elsewhere and in the future; informed agitation because in the absence of scientific understanding it is so easy to waste scarce political muscle on actions that end up having little impact or, like some biofuel mandates, to blunder blindly forward pushing development down even more destructive pathways.

Informed agitation: the arousing of public concern about an issue, through the means of knowledge sharing, research, and deliberation for the purpose of bringing about action

Elements: variables or components of structure; may be coupled via functional relationships or processes

Sustainability science is one convenient term for the research community's contributions to the informed agitation required to address the challenges of sustainable development. The pool of potentially relevant scholarship is vast and rapidly expanding. To bound this review, we have reluctantly forgone the temptation to sketch a history of sustainability science. We concentrate instead on the most recent work we know that captures the state and frontiers of sustainability science at the dawn of the third decade of the twenty-first century, relying on those publications we do cite to credit the foundational studies on which current understanding has been built. We focus on the subset of research on sustainable development that seeks to produce generalizable guidance for use in practical problem solving, i.e., that resides in what historian Donald Stokes has termed Pasteur's quadrant (15). This means that we give short shrift to the important foundations of sustainability science that were built from curiosity-driven basic research in a variety of disciplines ranging from ecology to economics to history (i.e., work in Stokes's Bohr's quadrant). An overview of that work is available elsewhere (16). We also stop short of reviewing the application of sustainability science to solve particular problems in particular contexts (i.e., work in his Edison's quadrant). Reference 17 provides a taste of that vast body of applications work, ranging from the management of irrigation systems in Nepal to the promotion of energy transitions in Europe.

Even with our drastic bounding of this review to contemporary sustainability science centered in Pasteur's quadrant, there are other questions we could have investigated, other interpretations we could have considered, and other publications we could have cited. Moreover, the field as a whole is growing so (gratifyingly) quickly that any review—ours included—will rapidly lose its currency. As one response to these limitations, we have established an open-access website to complement this review (see **http://sustainabilityscience.org**). The site currently provides an expanded treatment of the argument we present here. We will endeavor to update it as the field and our understanding of it continue to mature. Input and feedback from readers of this review will be vital for making this experiment useful and timely: Please check it out and let us hear from you.

1.3. Organization of the Review

We begin this review with a survey of the interdisciplinary research programs that have most shaped our understanding of sustainable development over the past several decades. From these programs, we extract a union set of elements (variables) and relationships (interactions) that have proven particularly powerful in illuminating sustainable development in at least some contexts. These, we argue, are plausible candidates for consideration in future work aimed at crafting generalizable theory and models in sustainability science. We synthesize them in an integrative Framework for Research in Sustainability Science that we hope will help researchers better communicate and collaborate with one another as the field continues to mature.

In Section 2 we summarize research showing that nature and society in the Anthropocene have become intertwined in a globally interconnected, complex adaptive system. The heterogeneity, nonlinearities, and innovation characterizing that system generate development pathways that cannot, even in principle, be fully predicted in advance. The central implication of this finding, still not as widely appreciated as it should be, is that sustainable development can realistically be pursued only through an iterative strategy that combines thinking through and acting out (18). That is, effective strategies for the pursuit of sustainability must certainly use science to help identify and create interventions likely to promote sustainability but must also foster capacities to put those interventions into practice, monitor and evaluate the results, and take corrective action in an iterative and open-ended pursuit of sustainable development. Research has identified six such capacities. We list these in the abstract and Table of Contents and explore what is now known of their character, strengths, and limitations in Sections 3–8. We conclude with summaries of some of the most useful generalizable knowledge that sustainability science has produced over the past two decades and some of the central challenges the field faces in the years ahead.

Frameworks: the most general form of conceptualization in science; provide checklists or building blocks for consideration in constructing theories or models

2. AN INTEGRATIVE FRAMEWORK FOR SUSTAINABILITY SCIENCE

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 (19). Although 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 review. 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 are usefully thought of as the most general form of conceptualization in science (19). They provide checklists or building blocks of elements and relationships 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

[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 that we hope interested readers will find useful. (Follow the **Supplemental Materials** link in the online version of this article or at **http://www.annualreviews.org/**.)

Supplemental Material >

Table 1 Research programs that have shaped sustainability science

Name(s)	Special contribution(s)	Recent review(s)
Complex adaptive systems (CAS)	Local action by heterogeneous (diverse) agents, constrained by higher level structures, central role of innovation/novelty	20, 21
Coupled human and natural systems (CHANS)	Reciprocal links between human and natural systems, special attention to links across space	22
Coupled human-environment systems (CHES)	Place-based analysis of linkages, emphasizing physical and biotic environment; actors and agency	23
Earth system governance (ESG)	Highlights importance of institutional design, agency, and power for governing nature–society interactions; emphasis on transitions and inequality	24
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	25, 26
Environmental justice (EJ)	Focus on inequality and environmental harm, highlights vulnerability of poor and marginalized communities to pollution, maldistributions of power	27, 28
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	29–31
IPBES conceptual framework	Focus on biodiversity benefits for people, collaborative processes for fair mobilization of multiple value, multiple knowledge systems	32
Livelihoods	Local actors' entitlements and capabilities to secure access to resources and their benefits; role of agency, power, politics, and institutions	33
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	34
Resilience thinking	Intertwined social/ecological systems as CAS displaying multiple regimes, tipping points, fast versus slow variables, coping with risk, adaptive capacity	35
Social-environmental systems	Co-production of useful knowledge by actors and analysts, boundary work, trust, power, monitoring, feedback for adaptive management	36
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	37
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	38, 39
Sustainable consumption-production (SCP)	Beyond control of pollution from production alone or consumption lifestyles alone to joint consideration of coupled consumption and production activities	40, 41
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	42, 43

ongoing efforts to construct and test middle-range theories about how to promote sustainable development (44). 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 section 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 sections explore how these concepts have been used to inform agitation for sustainable development.

Pathways of development: temporal changes in patterns of observed or predicted covariation in nature and society

2.1. 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: environment and development, governance, complexity, and context dependence. In Section 2.2, we integrate this description in a Framework for Research in Sustainability Science (see **Figure 1**, in Section 2.2).

2.1.1. 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 review.

2.1.1.1. Nature–society interactions.[2] 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 (35). 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.

2.1.1.2. 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 occupy 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 (4). The Sustainable Development Goals (SDGs) recently articulated under the auspices of the UN have reaffirmed this overarching goal (45). They have also, however, somewhat muddied 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 (43).

2.1.1.3. Resources. 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

[2] 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 sociotechnical interactions (which connote to many a diminution of the importance of nature in the Anthropocene System).

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 (46), e.g., biodiversity, ecosystems, the physical environment (e.g., climate), and minerals. Others are anthropogenic, or made by people (47), 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.

Capital assets: resource stocks—both natural and anthropogenic—on which society draws for its well-being

Governance: the arrangements by which any collectivity, from the local to the global, seeks to manage its common affairs

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)

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

Power: the ability of actors to deploy their agency in ways that affect the beliefs or actions of other actors

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

2.1.2. Governance. A second part of the Framework asks how nature–society interactions respond to governance: the arrangements by which "any collectivity, from the local to the global, manages its common affairs" (48, p. 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 (37). The elements and relationships bearing on governance that have received the 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 the review.

2.1.2.1. Actors. Actors in the Anthropocene System come from both the natural and social subsystems. The former has been construed to include some nonhuman 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 (49). Characteristics of social actors that have proven salient for sustainability science include their values, beliefs, empathy, interests, capabilities for learning and innovation, and power.

2.1.2.2. Institutions. Institutions 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 (50). 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 (51)—have affected or are likely to affect the prospects for achieving sustainability goals.

2.1.2.3. Power. Power is the ability of actors to affect the beliefs or actions of other actors (52). Power can both constrain and enable what people think and do (53). 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.

2.1.3. 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) (21). Three fundamental attributes of the Anthropocene make it a complex adaptive system: the persistent heterogeneity (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 (54). 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 (55).

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)

2.1.3.1. Hierarchical organization. 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).

2.1.3.2. 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 (56, 57). 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 (58). The implications for sustainability of treating novelty seriously are profound and explored further in Section 6.

2.1.3.3. Horizontal connections. 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 (59). Studies of horizontal connections have also addressed the propagation of disturbance and novelty through the Anthropocene System (60–62). More generally, studies of both teleconnections among people, materials, information, and places (22) and of social connections in actor networks (63) are generating sufficiently useful insights to suggest that horizontal connections should be considered in most new studies for sustainability science.

2.1.3.4. Vertical connections. Vertical connections[3] 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.,

[3] 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.

work on driving forces (64), path dependencies (65), and other slow variable processes such as climate change and globalization (66, 67). 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 (68). Increasing attention is also being given to the role of polycentric connections across levels and elements of governance in guiding action for sustainability (69).

Polycentric: systems with multiple sources of partial authority and semiautonomous decision-making that interact to create multi-level governance arrangements

Regimes: sets of dominant relationships (both natural and social) that give rise to characteristic dynamics and development pathways

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

2.1.3.5. Far-from-equilibrium dynamics. Far-from-equilibrium dynamics are the norm, not the exception, in the complex adaptive system of the Anthropocene. These dynamics exhibit multiple regimes, or characteristic sets of behaviors driven by a particular set of dominant relationships, feedbacks, or rules of the game.[4] 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 (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 (70–72).[5] 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 (73). Finally, because multiple regimes exist in the Anthropocene System, multiple opportunities exist for interactions or interplay among them (75) and for cascading regime shifts within and across hierarchical levels (76, 77). One of the most exciting additions to sustainability science over the past decade has come from a vibrant community of researchers that originally studied historical regime transitions in sociotechnical systems, but that is now contributing directly to understanding pathways toward sustainability (38). We review this work in Section 6.

2.1.4. 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 (78, 79). 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 (44).

2.1.4.1. Action situations. 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

[4]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.

[5]We follow Scheffer (73) 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 to a change in dominant feedbacks. See a discussion in Reference 74 for a review of how these terms are used in the literature.

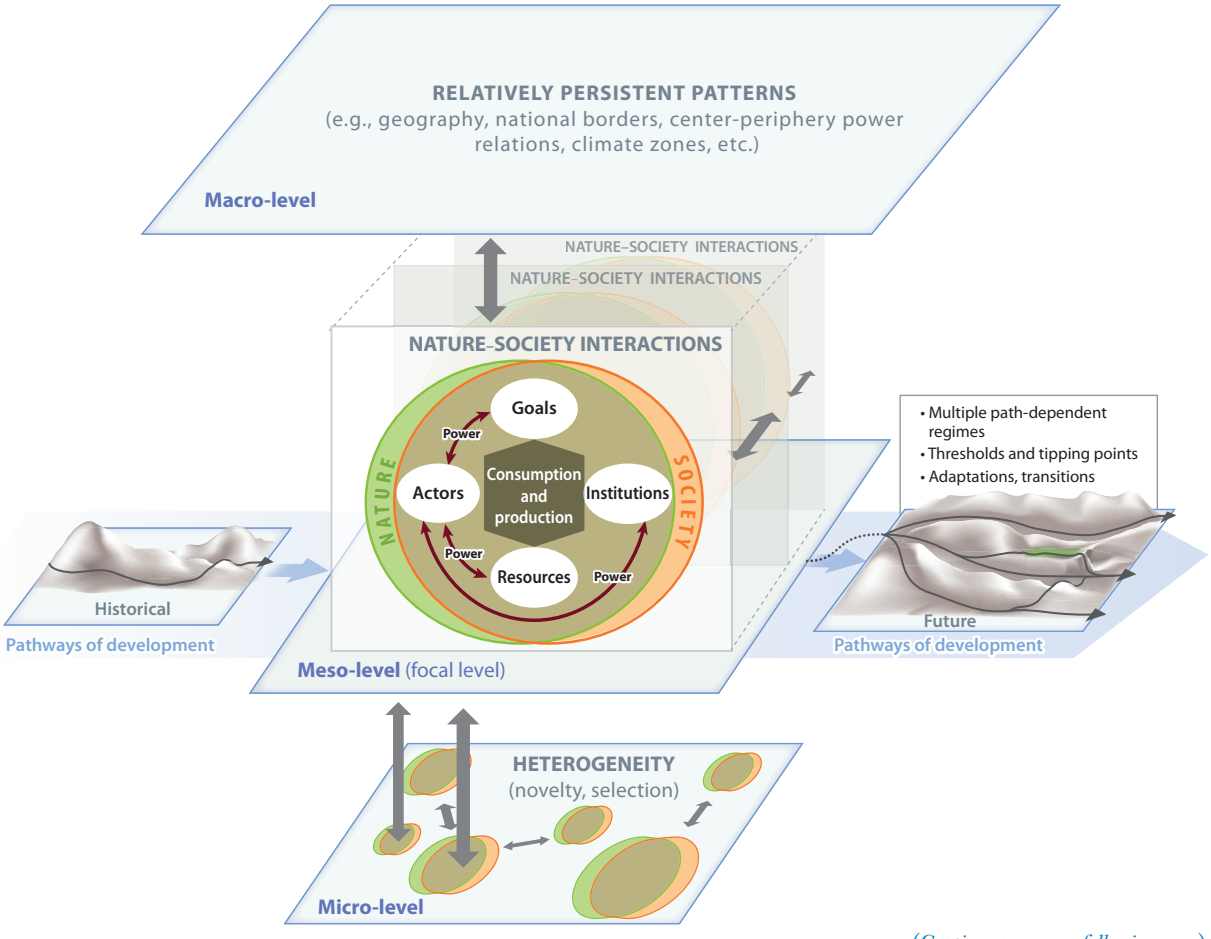
researchers and analysts to "bound the problem" by explicitly identifying which temporal and spatial scales, elements, and relationships are explicitly treated "inside" a particular study, and which are provisionally set "outside" or otherwise excluded. One of the most fully articulated approaches to 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 (37). 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 (80). It is in this broader sense that we use the term action situation when addressing the importance of contextualizing sustainability science.

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

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 (81), poverty traps (82), land use change (44), energy transitions (83), and urbanization (84). Most such middle-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).

2.1.4.2. 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) that in turn draw on, and may reinvest in, the underlying resource base (e.g., land, labor). The literature that has focused most consistently on such action situations contextualizes the complex, multi-level character of nature–society interactions in terms of sustainable consumption and production (85). Sustainable consumption and production has also emerged as the single most widely shared component of the UN's SDGs (86). Much of the relevant research still focuses on one end of the relationship or the other, with consumption studies emphasizing the role of actors' values, incentives, and practices (87) and production studies emphasizing efficient and even circular use of resources (e.g., 88). Increasingly and encouragingly, however, scholars are exploring action situations for sustainable development in terms of truly integrated approaches to consumption and production (40).

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 relationships are generally in play, drawing on the same resources for different purposes and thereby affecting the challenges and opportunities facing one another (80). The resulting nexus of interacting action situations has proven extremely difficult to untangle (89) and stands as a frontier challenge for efforts to integrate research on sustainability (90).



(*Caption appears on following page*)

2.2. Integration: A Framework for Research in Sustainability Science

Section 2.1 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 is admittedly a long and potentially confusing checklist. 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 be determined only 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 (*Figure appears on preceding page*)

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).

3. CAPACITY TO MEASURE SUSTAINABLE DEVELOPMENT

One of the greatest and longest-standing challenges facing sustainability science has been to design and implement methods for measuring sustainable development. As characterized by Partha Dasgupta in his seminal work on the subject (91), the measurement challenge takes two forms: valuing recent pathways of development and evaluating the likely impact of policies or other interventions on future pathways of development.

A vast array of metrics has been used to value and evaluate development pathways. These range from GNP to carbon emissions to the Human Development Index to the UN's SDG metrics. Most capture something relevant to sustainability; none captures everything (92). Fortunately, one of the strongest contributions of science to sustainable development over the past two decades has been the beginnings of an integrative, theory-grounded, and useful capacity to measure one central feature of sustainability: the adequacy of the resource base to support human well-being now and in the future. Systematic efforts to assess the resource base, grounded in both theory and empirical work, are now being advanced on numerous fronts under the general banner of "Beyond GDP" (4). The variant of these approaches to measurement that has resonated most deeply with the sustainability science community is that on inclusive wealth, recently summarized in a series of comprehensive reviews (42, 93–95). We sketch the current state of play on inclusive wealth metrics in the remainder of this section, highlighting relevant assumptions, applications, and remaining challenges.

3.1. Findings: Well-Being, Resources, Capital Assets, and Inclusive Wealth

Productive base: the total set of resource stocks or capital assets on which society draws for its well-being

Measuring sustainable development in terms of its ends is formally equivalent to measuring it in terms of the means for achieving those ends. In particular, measuring sustainability in terms of its goals of inclusive well-being is formally equivalent to measuring it in terms of the inclusive wealth that constitutes the productive base on which people draw to achieve those goals. Both theory and experience suggest, however, that for measuring sustainable development over long periods it is generally easier to measure the stocks of resources that function as its determinants (means) than it is to measure the flows of goods and services that are consumed as constituents of its ultimate end, i.e., inclusive well-being (43).

The particular stocks that must be conserved can usefully be seen as the resources highlighted in many of the analytic frameworks discussed in Section 2. The theory behind this view builds on a long tradition of work in welfare economics and the economic theory of capital. It portrays resources as the capital assets that constitute the productive base on which people in the Anthropocene System draw to produce the goods and services that they then consume to advance their well-being. As noted in Section 2, some of these resources (assets) are considered natural in that they are directly derived from nature, whereas others are considered anthropogenic or constructed by people. Subdivisions of these major resource categories that have been particularly useful in sustainability science research are listed and illustrated with an example in **Table 2**. The key insight for sustainability science is that both natural and anthropogenic resources (assets) are necessary to produce well-being, just as the fishing community of **Table 2** requires both fish and boats to prosper.

The resources that are most important in a given case will always depend on context, as suggested by the second column of **Table 2** and the more general examples of the third column. But research suggests that the resources shown in the table can usefully be thought of as the fundamental determinants or state variables underlying the generation of peoples' well-being in the Anthropocene System. A significant body of research has now accumulated exploring the character of each of the general resource categories listed in **Table 2**: What enhances them, what depletes them, and how do they benefit society (see the fourth column, "Recent reviews")? Sustainability science should build on this progress, moving beyond a preoccupation with single resources and aiming to assess the potential contributions to sustainability from each of the basic resource categories summarized in **Table 2**, as well as the interactions among them.

Table 2 Resource stocks that constitute the productive base for human well-being

Resource group	Specific example of an ocean fishery	General list of representative resource stocks	Recent reviews
Natural capital			46
Ecosystems	Fish and their food	Biota, biomass, communities	12
Environment	Ocean temperature, pH	Climate, quality and quantity of land, air, water	96
Minerals	Fossil fuel for the boats	Fossil fuels, iron, sand, etc.	97
Anthropogenic capital			47
Manufactured capital	Boats of the fleet	Roads, buildings, infrastructure	98
Human capital	Skilled fishers	Population; its health, education, distribution	99
Social capital	Regulations on catch	Institutions (including rules, norms, rights, culture, networks, etc.)	100, 101
Knowledge capital	Maps of the seabed	Indigenous, practical, scientific	102, 103

3.1.1. Inclusive wealth in theory. Inclusive wealth theory has built upon the foundational research findings noted above to create a rationale for the following proposition:

> *For a development trajectory to be sustainable, a necessary condition is that it conserve inclusive wealth, defined as the per capita social value, adjusted for distribution, of the full array of resource stocks that constitute the productive base of the Anthropocene System.*

The full elaboration of the argument behind this proposition is subtle and merits more attention than we can provide here. The reviews cited at the beginning of this section provide the details. Important features of inclusive wealth that are addressed in those reviews include the following:

- Well-being of people is a central goal or end objective of sustainable development. It has multiple constituents, the importance of which will vary across people and generations. Measuring well-being directly is highly problematical. Under a plausible range of conditions, however, per capita well-being is tracked by per capita wealth.
- Wealth is a means to the end of creating social well-being. It consists of resources, both natural and anthropogenic, that together constitute determinants of well-being. Wealth is neither the total amount of resources nor their monetary value. Rather, it is the estimated social value of those resources, i.e., what they can contribute as means for the creation of well-being.
- The social value of resource stocks to particular social actors depends on context, in particular where and when they live, their goals for sustainability, and how they define what well-being means for them.
- Inclusive means everyone's: not just aggregate quantities of resources, but actual access by relevant actors to those resources (or the goods and services they produce); not just resource endowments here and now, but also across relevant places and generations. Aggregation weights for individual actors' wealth can be designed to reflect society's commitment to equity in sustainable development (see Section 4).
- Conserving inclusive wealth means that it does not decline with time, i.e., that each generation passes on to the future (at least) as much inclusive wealth as it received from the past. Note that in general many alternative bundles of resources will meet the conservation criterion for sustainability.
- Inclusive wealth is always about forecasts: What value could society expect to produce from a specified endowment of resources given a particular understanding of how (relevant parts of) the Anthropocene System works? Which actors have the power to make it work for them? Good measures of inclusive wealth therefore require deep scientific understanding of the dynamics of the Anthropocene System.
- Estimates of inclusive wealth are only about the potential of the relevant system to produce well-being. This potential may not be realized in practice if the assumptions of the forecasting model turn out to be wrong or if people lack the other capacities addressed later in this review.

3.1.2. Inclusive wealth in practice. Practical applications of inclusive wealth concepts have begun to accumulate. These include a growing array of science-grounded assessments of the sustainability of recent development patterns (104). They have been carried out by individual scholars (105, 106), by nongovernmental organizations (107), and by the World Bank (108). The initial focus on national-level measures is now being complemented with an increasing number of local and regional valuations (e.g., 109, 110). Moreover, the theory is beginning to be employed in

prospective evaluations of alternative policies for promoting sustainability in cases ranging from alternative scenarios of national development (111) to massive desalinization for the production of drinking water (112) to substituting anthropogenic for natural capital (113) to mitigating the risk of collapse of the Greenland ice sheet (114). Much remains to be done. But the current state of research and application on inclusive wealth represents a significant advance over a past in which sustainability was whatever those claiming to pursue it wanted it to be.

Risk: the prospect of loss or gain under uncertainty of something thought to be of value, often incorporating estimates on the likelihood of a change and consequences if the change occurs

(In)equity: a normative concept referring to the qualities of justness, fairness, and impartiality

3.2. Building Capacity: Resources, Capacities, Connections, and Equity

The challenges of fully developing and operationalizing research-informed but practically useful measures of sustainable development remain substantial. Three merit particular attention.

3.2.1. Valuing resources. A combination of methods and models are now being employed to provide useful estimates of the social value or inclusive wealth represented by resource stocks. Some are anchored in the social deliberation (115), others in systems simulation (112), and still others in market prices supplemented by science-informed calculation of the true value to society (also called shadow or accounting prices) of resource-based goods and services that are not traded in markets (116). Current value estimates are relatively solid for resources traded in markets (e.g., minerals and houses), improving rapidly for ecosystems, and almost nonexistent for less tangible resources such as social capital (but see 117). Building a capacity for integrated valuation of all relevant resources in particular contexts should be a central task of future research in sustainability science.

3.2.2. Valuing operational capacities. This review argues that in addition to the conservation of inclusive wealth, a variety of operational capacities are necessary for the pursuit of sustainability. We discuss these capacities at some length in subsequent sections of the review. As is the case for resources, social actions can either deplete or strengthen each of these capacities. For none of them, however, are good measures of their social value yet available. Informed choices regarding the relative merits of investments in the respective capacities are thus impossible. Research to rectify this situation by creating good measures of the operational capacities discussed in the following sections is urgently needed (42).

3.2.3. Accounting for connections. Connections among heterogeneous units of the Anthropocene System are now generally accepted to be important determinants of system behavior and sustainability (see Section 2 and **Figure 1**). This importance clearly ought to extend to inclusive wealth accounts. To date, however, virtually all of the theory and empirical work on inclusive wealth ignore connections that move wealth within and across levels of system organization. This shortfall seems more one of neglect than of inherent conceptual difficulty. It should thus be a ripe area for future research in efforts to develop a mature capacity to measure sustainable development.

We further explore the governance challenges of measuring sustainable development to nurture shared resources in Section 8.2.

4. CAPACITY TO PROMOTE EQUITY

We argue in this section that a greater capacity to promote equity is necessary for the effective pursuit of sustainable development. (In)equity is a normative concept dealing with fairness and

justice that has been central to social deliberations on sustainability. In that context it addresses how fairly people judge the fruits of the Earth's resources are being distributed within and between generations. (In)equality is a positive concept used for describing those distributions. (In)equality in access to resources is an emergent property of the Anthropocene System that can be modified through policy to meet the equity component of sustainability goals. Power differentials among actors turn out to be both a cause and a consequence of inequality. Empowerment of those actors who are losing out under current pathways of development is thus a vital component of the capacity to promote equity in sustainable development.

(In)equality: a positive or descriptive concept referring to the distribution of assets or freedoms among actors

4.1. Findings: (In)equity, (In)equality, and Power

The Brundtland Commission put (in)equity and (in)equality at the core of its case for sustainability, arguing that inequality is both the "planet's main 'environmental' problem" and its "main 'development' problem" (3). Subsequent international deliberations have reaffirmed this perspective with specific emphasis on sustainability as fairness, its goals including both the alleviation of poverty in today's world and the assurance that efforts to improve well-being today do not unfairly undermine the prospects of those seeking it tomorrow (45). These normative commitments to equity have also been used to argue that all people deserve the freedom and capacity to pursue their own visions of the good life (5).

4.1.1. (In)equity. Given the centrality of concerns over (in)equity to the political deliberations about the goals of sustainable development, we were surprised to discover how relatively little those concerns have figured into sustainability research or practice during most of the period covered in this review. There have always, thankfully, been a few welcome exceptions (e.g., 118). But only recently have equity concerns begun to appear consistently in sustainability scholarship (e.g., 106, 119, 120). And even when research has addressed equity issues, as is true for the inclusive wealth scholarship discussed in Section 3, applications have lagged behind. For example, none of the UN or World Bank reports on historical patterns of inclusive wealth we cited there (107, 108) give more than passing attention to the questions of intragenerational equity latent in their data. Even more surprisingly, none of the 17 UN SDGs explicitly addresses the concerns of intergenerational equity that have been so central to sustainability discourse (121, 122).

Society cannot achieve the goals of sustainable development that it has repeatedly endorsed without giving more attention in both research and practice to the challenges of achieving fair and just distributions of well-being both within and between generations. We therefore conclude that a second necessary (but not sufficient) condition for sustainable development is a greater capacity to promote equity within and between generations. In the remainder of this section we summarize the research that we have found most relevant to advancing the equity dimension of sustainability. References 123–126 provide deeper treatments of key topics than we can cover here. We have drawn heavily on them in shaping our argument.

4.1.2. (In)equality. Both theory (127) and empirical evidence (125) suggest that substantial inequality is an emergent property of the Anthropocene that should be looked upon as the rule, not the exception, for pathways of development. Multiple inequalities relevant to sustainability exist with opportunities and outcomes divided by income, race, class, gender, ethnicity, nationality, and other factors. Moreover, these inequalities frequently intersect with and reinforce one another (128). Scholars have documented the ways in which quantifiable metrics of inequality are distributed over time and among actors within and between different action situations (129–132).

Inequality has a tendency to snowball such that without intervention unequal wealth distributions become even more unequal over time (123). Understanding inequality therefore requires a multi-generational historical perspective (133). This historical record shows that patterns of inequality change over time and can be both strengthened and mitigated by anthropogenic and natural influences (129). Mitigating influences include micro-processes of accumulation and distribution (134) and macro-forces including wars and natural calamities (135). Perhaps most relevant for action to promote sustainable development are findings on the efficacy of meso-level institutional structures (129, 136). Some of these can reduce inequalities, including inheritance taxes and strong unions (137). Others have been shown to accentuate them: tax systems that target wages over investment income, as well as ownership of intellectual property and stocks of scarce natural resources (138). That said, many mechanisms that reduced inequality through much of the twentieth century in the affluent West—e.g., increasing access to education, rural-urban migration, and progressive tax systems—seem to be no longer functioning as mechanisms of redistribution (131).

4.1.3. Power. Some inequalities would result from the heterogeneous distribution of resources in the Anthropocene System even if all actors preferred an equitable allocation. But all actors do not. Indeed, initial inequalities are reinforced by a variety of mechanisms, ranging from what psychologists call social dominance theory (a preference to prefer inequity over equity; 139) to the norms of capitalism to realist strategies of states. What these mechanisms have in common is power, a fundamental relationship in the Anthropocene System that we defined in Section 2.2 as the ability of some actors to affect the actions and beliefs of others.

Access to resources (including each of the resources discussed in Section 3) is at the heart of individual power (140, 141). Inequality in the access to resources leads to inequalities of power that in turn reduce the abilities of all but the most powerful actors to define and pursue their own goals. For example, the ability of colonial governments to extract vast quantities of resources (including slave labor) from their colonies, promoting their own well-being at the expense of others, was predicated on unequal distributions of military and economic resources and therefore power (130, 142).

The literature on power, however, shows that it can take many forms that go well beyond coercive power derived from superior military or economic might. In response to the increasing awareness that maldistributions of power reinforce unsustainable development pathways, more and more sustainability science research is seriously grappling with the mechanism and impacts of power on development pathways (e.g., 126, 143–145). Yet this literature remains disjointed, failing either to build on itself or to converge around a common theoretical language with which to discuss the mechanisms of power (53). Our review of the core political and sociological approaches to the study of power, as well as more recent work on power and sustainable development, leads us to conclude that future work in sustainability science would be well served to build on an adaptation of a three-dimensional view of power first articulated by Steven Lukes (146). We advocate Lukes's approach both because it is frequently used to conceptualize the mechanisms of power in empirical work and because, by articulating power's relationship between actors, resources, institutions, and goals, it fits well within the Framework for Sustainability Science we described in Section 2 and **Figure 1**.[6]

[6]Another useful perspective on power emphasizes relational power and the dynamics of synergy, antagonism, and neutrality that emerge when different actors possess different kinds of power in relation to one another (145).

Lukes (146) proposes three dimensions of power, each of which provides an entry point for advancing the equity dimensions of sustainable development:

1. Compulsion: This dimension of power is derived from actors' ownership of or access to natural and anthropogenic resources and/or flows of goods and services produced from those resources. It gives powerful actors the ability to compel relatively powerless actors.
2. Exclusion: This dimension of power is derived from actors' ability to shape institutional structures, including rules and norms to serve their own interest, often at the expense of other actors. It gives powerful actors the ability to exclude relatively powerless actors from decision-making processes.
3. Influence: This dimension of power is derived from the ability of actors to shape the goals, aspirations, values, and even knowledge systems that privilege the well-being of some actors over others. It gives powerful actors the ability to influence relatively powerless actors.

Incumbency: relationships among actors and institutions through which power differentials shape, stabilize, and reinforce existing regimes and their associated development pathways

We explore the implications of this perspective for understanding prospects for empowerment in Section 4.2.

4.2. Building Capacity: Empowerment of Current and Future Generations

Inequality and resultant maldistributions of power hamper the prospects for sustainable development along multiple dimensions. Within the current generation, research demonstrates important if complex relationships between poverty and maldistributions of power in overexploitation of natural resources and worrisome patterns of resource use (79, 82). And unchecked corporate power has enabled private interests to discredit science and delay action on issues from toxic chemicals to global warming, thus harming both present and future generations (147). Indeed, the persistence of many seemingly intractable global problems, from the climate crisis, to ecological destruction, to persistent poverty in a time of plenty, can in many ways be attributed to incumbency: the relationships among actors and institutions through which power differentials shape, stabilize, and reinforce existing regimes and their associated development pathways (148).

The pursuit of sustainable development is thus a political agenda that requires redistribution of access to resources, and to the flows of benefits from those resources, both within and between generations. To do this, those agitating for sustainable development will have to overcome the resistance of incumbent actors keen on stabilizing current regimes and their associated development pathways. Doing so will almost certainly require conventional top-down efforts by reformers in government and industry. But top-down strategies alone are unlikely to be sufficient for two reasons. First, top-down efforts risk violating Sen's admonition, quoted earlier, to see people not as patients but as agents with the potential to set goals and agendas of their own. Second, elite capture of top-down governance approaches is well-documented (149–151). For these reasons, realizing a vision of sustainability as fairness will require work to empower the individuals and groups that are most harmed by current development pathways: today's vulnerable communities and future generations. Building a capacity to promote equity is thus a second necessary condition for the effective pursuit of sustainability.

Collective social movements are likely to play a fundamental role in efforts to promote intra- and intergenerational equity (152). Scholarship on empowerment is beginning to sort out which strategies for overcoming maldistributions of power are most likely to be effective in particular action situations (153). Much of this scholarship has found Lukes's three-dimensional perspective on power useful because it provides a language with which to analyze path-dependent regimes, the cross-level linkages that often serve to reinforce incumbent interests, and the spaces and leverage points available to shift development pathways toward more equitable outcomes (154).

POWER AND EMPOWERMENT IN APPALACHIA

John Gaventa's classic study of power in a central Appalachian valley demonstrates how compulsion, exclusion, and influence serve to reinforce one another (155). Through his analysis, he shows that when the powerful owners of the local mine began to lose their grip on one dimension of power, they were able to mobilize their control over the other two dimensions to protect their interests until they could reestablish control over all three dimensions. Successful resistance was possible only when agitators strategically mobilized against all three dimensions of power. They did this through collective issue framing to identify inequities (third dimension of power), formulation of specific demands for changes in rules and norms and identification or creation of venues for protest and participation (second dimension of power), and open protest and conflict over the resources from which the coal company drew its power (first dimension of power).

The explanatory value of the three dimensions of power in analyzing strategies of empowerment was perhaps most famously articulated by John Gaventa in his 1980 study of Appalachian coal country (see the sidebar titled Power and Empowerment in Appalachia). More recent efforts to mobilize against all three dimensions of power can be seen in struggles to promote sustainable development. Activists often initially turn to the third dimension of power in efforts to alter path-dependent regimes reinforced by the interests of powerful actors. For example, in Latin America, maldistributions of power were reinforced by norms that legitimized inequities. Activists disrupted these norms by mobilizing marginalized groups around new concepts of justice and fairness. Over multiple decades, new norms of fairness contributed to the restructuring of institutions that reduced inequality in Latin America in the early years of the twenty-first century (156). Strategic use of the second dimension of power has also been made by activists and agitators. They mobilize local governance mechanisms, the court system, and legislative pressure to change laws and regulations to reinforce gains made through struggles over the third dimension of power (157, 158).

Efforts to mobilize the first dimension of power by regaining access to resources are often the most challenging for disempowered actors. Indeed, empirical evidence from real-estate markets in the United States shows that the same asset, when it belongs to a member of a marginalized group, can be devalued in the market simply by virtue of the fact that it is owned by a member of a marginalized group (159). Nevertheless, examples of efforts by indigenous communities around the world to secure land redistribution and formal land tenure show that occasionally activists can successfully regain the first dimension of power, but these efforts are almost always predicated on strategic use of the second and third dimensions of power (160, 161). Current efforts by activists to influence the banking and insurance industries to stop supporting fossil fuel companies are also designed to deprive incumbent actors of the first dimension of power by limiting their ability to finance extraction of fossil fuels (162).

How to empower future generations in current decision-making remains a topic of continued theoretical and practical discussion. Theoretically, as illustrated by debates over appropriate discount rates to use in climate policy, scholars continue to argue about how best to compare present and future well-being and whether it is warranted to assume that future generations will be wealthier and have better technologies (163). Practically, suitable legal and regulatory mechanisms are still being developed and tested to ensure whatever rights we grant to future generations are in fact honored by today's decision-makers (157). More empirical research on strategies for empowerment of current and future generations, together with legal, regulatory, and behavioral approaches to promoting intra- and intergenerational equity, will almost certainly prove necessary

in the pursuit of sustainability. In Section 8.2 on building governance capacity, we further explore the research on governance strategies to promote equity, looking specifically at the role of values and norms; laws, rights, and regulations; and social movements as tools to foster more equitable development pathways for both current and future generations.

5. CAPACITY TO PROMOTE ADAPTATION

Adaptation has long been an important focus of sustainability science, addressed by a broad range of research traditions. Scholars of risk have highlighted the deep and interlinked uncertainties that are a common property of the Anthropocene System and latent in all nature–society interactions (164). Scholars of vulnerability have focused on places or subpopulations likely to lack or lose access to the resources needed to secure people's well-being in the face of threats (165). Resilience researchers have explored how the characteristics of the Anthropocene as a complex system both support and constrain adaptation (166). Research on innovation (167) and complexity economics (168) have emphasized how uncertainty and disturbance provide not just threats but also opportunities for novel ways of using resources to advance well-being.

Our review of these various research programs found substantial potential for complementarity among their insights. That potential has often remained unrealized, however, due to siloed scholarship and a related proliferation of different terminologies for similar concepts. We do not seek to adjudicate those differences here but rather aim to highlight the substantive findings that lie beneath them. Our overall conclusion is that an additional necessary condition for sustainable development is the creation and maintenance of a substantial adaptive capacity. We find it useful to distinguish the capacity to adapt from the related capacity to transform on the basis of their relationship to regimes. For our purposes here, we define adaptive capacity as the ability to confront potentially disruptive change in ways that keep the system operating within its current regime and thus on something like its current development pathway. Transformative capacity, in contrast, can usefully be seen as the ability to shift a system between regimes, e.g., out of regimes supporting unsustainable pathways of development and into regimes supporting sustainable ones. We defer our exploration of research on the capacity to promote such transformations to Section 6.

5.1. Findings: Risk, Vulnerability, and Resilience

The past two decades of research on topics related to adaptation have built a foundation of findings on which efforts to enhance adaptive capacity for sustainable development can build. We cannot do justice here to that rich array of findings. Instead, we summarize three fundamental results that we find to be of particular importance for sustainability. We refer readers interested in the evidence behind these results to several excellent reviews on which we have drawn extensively (see 169–171).

5.1.1. Adaptive capacity is necessary for sustainable development. The Anthropocene System is invariably full of disruptions: shocks, surprises, novelty, and the unfolding unknown (172). This implies that even development pathways that are considered sustainable now will eventually be pushed in unsustainable directions. Moreover, assessments concluding that certain future development pathways should be sustainable will eventually turn out to be wrong (e.g., due to uncertainty or external shocks or internal novelty) and thus will require adaptive corrections. The research challenge is to better understand how such adaptive capacity functions, and how it can be strengthened, maintained, utilized, and evaluated.

Adaptation: response to potentially disruptive change that seeks to limit damage or seize opportunities for improvement to a development pathway within a regime (contrast with transformations, resilience)

Vulnerability: the likelihood that a particular subpopulation will lack or lose access to the resources they need to secure their well-being in the face of disruptions

Resilience: a system's ability to utilize the "breathing room" provided by its robustness to disturbance to fundamentally change how it uses resources under the new conditions (see also adaptation, transformations)

Innovation: the interplay of actors, institutions, goals, and resources through which new artifacts and practices are invented, selected, adapted, adopted, and brought into widespread use

Disruptions: shocks, surprises, innovation, and the unfolding unknown

Adaptation pathways: dynamical, and typically path-dependent, sequences of adaptations in which early adaptations influence the conditions that call for later adaptations

5.1.2. Adaptation capacity is dynamic. Early work on adaptation, vulnerability, and resilience generally focused on the capacity to produce static assessments relevant to specific risks and action situations. More recent studies have shown that to support sustainable development the capacity to carry out such static assessments must be complemented with a capacity to carry out dynamical assessments focused on adaptation pathways (34). The argument behind this shift is simple but profound: Adaptations, like other attributes of complex adaptive systems, are path dependent, with each one setting in place a cascade of subsequent system reactions and adjustments (173). Moreover, the Anthropocene System will always be experiencing multiple adaptation pathways driven by multiple strategic actors working at multiple organizational levels in the context of multiple action situations. Some of these adaptation pathways will invariably interact with one another, further complicating the picture (174). Sustainability science should therefore strive to improve society's capacity to understand the dynamics of these multiple interacting adaptation pathways and to evaluate not just immediate local benefits of particular adaptive actions but also foreseeable responses to those actions by other actors elsewhere and later.

5.1.3. Adaptation pathways do not reduce risk so much as redistribute it. Adaptations often redistribute risk and vulnerability within the Anthropocene System rather than reducing it in any absolute sense. Research has shown a great variety of circumstances in which adaptations that mitigate immediate and local vulnerability do so by exporting it to other people, places, and times (175). The theory behind such apparent conservation of fragility is well established for linear control systems but still lacking for the nonlinear systems that characterize the Anthropocene (169, 176). A growing number of case studies, however, convincingly demonstrate how interventions to control short-term variability and associated risks arising from nature–society interactions can initiate adaptation pathways that systematically reduce adaptive capacity over longer periods and larger areas (e.g., 177). In particular, the discourse of climate change adaptation—especially in the context of development and developing countries—can reinforce existing vulnerabilities and power structures (178). Sustainability science should continue to broaden its perspective beyond short-term risk reduction to develop a capacity for guiding the risk (re)distribution and trade-offs that adaptation pathways seem inevitably to entail.

5.2. Building Capacity: Resources, Complexity, and Power

What determines adaptive capacity for the pursuit of sustainability? Research has demonstrated potentially important and interrelated roles for virtually all of the elements and relationships that characterize the Anthropocene as a complex adaptive system (see Section 2 and **Figure 1**). Five components stand out: resources, heterogeneity, connections, systems dynamics, and actors. The summary account of their roles we present here draws heavily on the reviews provided in References 20 and 179–181, to which we refer the reader interested in the detailed evidence.

5.2.1. Resources. Adaptation involves changing how resources are used in the face of disturbance so that they continue to yield a flow of goods and services commensurate with the pursuit of sustainability. Perhaps obviously but nonetheless importantly, the capacity for such adaptations is greater when resources—natural and anthropogenic—are more plentiful. Indeed, some scholars have argued that the same metric of capital assets that are being used in responding to the question "What must be sustained for sustainable development?" can also be used to respond to the question "Who has how much adaptive capacity for sustainable development?" (42). Other things being equal, richer is almost certainly safer (182). But questions of trade-offs remain and have not

been adequately illuminated by research: How much wealth should be committed to immediate well-being and how much to building adaptive capacity?

5.2.2. Heterogeneity. Heterogeneity is a defining characteristic of the Anthropocene System (see Section 2). It makes important contributions to adaptive capacity in at least two ways (20, 183, 184): by providing the potential for partially compensating losses in well-being resulting from disturbance to particular places or elements and by providing locally nurtured sources of novelty (biological variation, technological or policy innovation) that the larger system can draw on for dealing with post-disturbance realities in new ways.

Different kinds of heterogeneity—ranging from functional redundancy to fundamental diversity—have been shown to make distinctive contributions to adaptive capacity. In general, too little heterogeneity detracts from adaptive capacity. In particular cases, such as national crop yields, added diversity can have a significant stabilizing effect (185). Beyond that, however, the picture is less clear. Redundancy and diversity can compete with one another. And both can come at the cost of efficiency relative to more homogeneous systems well adapted to the circumstances of the moment. The challenge, as ever, is getting the balance right for particular action situations.

5.2.3. Connections. The potential contribution of heterogeneity to adaptive capacity can be realized only if it is complemented by appropriate connectivity. Connections, as noted in Section 2, are fundamental attributes of all complex adaptive systems. For the Anthropocene System, research has shown that patterns of connectivity—which elements are interconnected and how strongly—matter for adaptive capacity and can be manipulated to manage it. A sampling of relevant studies is provided in Reference 186. These show that in general either too much or too little connectivity can undermine adaptive capacity. A common resolution of this tension in complex adaptive systems is modularity: relatively tight connections among a selective subset of elements in ways that promote complementarities and efficiency, but with those modules relatively weakly and selectively connected to other elements of the system. However, the specific configurations of modularity that would best support adaptive capacity for sustainable development are poorly understood and almost certainly context dependent. Progress in resolving how connections can be managed to promote adaptive capacity has long been hindered by lack of theory-grounded language for providing nuanced characterization of connectivity patterns. That is now beginning to change with the application of network approaches to the assessment of connectivity in Anthropocene Systems (187). Even the best of this work, however, still struggles with dynamic assessments of how alternative network configurations should evolve to provide continuing support for the capacity to shape adaptation pathways under changing conditions (188).

5.2.4. Systems dynamics. The dynamics of nature–society interactions pose two related challenges that must be addressed in building adaptive capacity for sustainable development. The first is associated with the multiple timescales those dynamics entail, the second with their potential for non-reversibility. Reference 66 provides a sampling of relevant research papers. We summarize their findings here.

5.2.4.1. Multiple timescales. The dynamics of the Anthropocene System involve a variety of interactive processes operating at multiple timescales. Adaptations can, in principle, address both (relatively) fast and (relatively) slow dynamics. In practice, however, a variety of factors tend to favor adaptations that mitigate the immediate damages associated with fast variables—e.g., natural selection, human cognitive bias, and political short-termism. Too often, this means that the system ends up supporting adaptations to symptoms rather than adaptations that address the underlying

causes. Slow dynamics are left unaddressed and may even erode the capacity to guide adaptation pathways over the long run. The net result is that most of the adaptations actually undertaken often end up being too little, and too late, to support sustainable development. Research suggests that adaptive capacity to address the challenge of multiple timescales must include at least two components: the ability to create research knowledge about the dynamics of relevant slow processes and how they are likely to shape the long-term vulnerability of various components of the Anthropocene System (e.g., 189) and the ability to devise governance arrangements that can use such knowledge to support relevant adaptation actions on the ground (see Section 8).

5.2.4.2. Irreversibility. The second challenge for adaptation arising from systems dynamics is the potential for irreversibility or hysteresis latent in the Anthropocene as a complex adaptive system (190). Its significance is that trial-and-error adaptation, even in its most thoughtful adaptive management varieties, may fail to keep the development pathway within a desired regime. In principal, research can address this challenge by mapping relevant regimes and the thresholds separating them, determining which regimes lead to dangerous declines in inclusive well-being, evaluating the likelihood that adaptive strategies will be able to keep development pathways within desired regimes, and monitoring development pathways with a view toward providing early warnings that inform policy. Research summarized in the reviews cited at the beginning of this section has contributed to progress on building capacity for dealing with each of these tasks for particular action situations. That progress, however, has generally been modest. For example, relatively comprehensive mapping of relevant regimes has been accomplished for only a very few action situations (e.g., 44, 77). Talk about planetary boundaries has gotten far out ahead of what science can justify, often confusing normative issues of risk tolerance with the scientific (but poorly understood) mapping of thresholds separating alternative regimes (191–193). Promising theoretical work on the prospect that appropriate monitoring could detect early warning signs when dynamics are approaching boundaries has proven feasible at the level of organisms and their health but enormously challenging to implement at the level of nature–society interactions (194).

5.2.5. Power. Who benefits and who loses from the redistribution of risks that occurs along adaptation pathways is not random. Rather, as already discussed in Section 4, it is determined by the continuing coevolution of nature and society within which some people have more power than others. Power shapes how risks are articulated, causation is attributed, adaptations are formulated, decisions are made, and outcomes are evaluated (170, 173). The result has been a highly inequitable distribution of risk and vulnerability at all levels of organization: household, community, regional, and national (179). Human agency matters in shaping this distribution (e.g., 174). But it is usually the actors with power who have greater capacity to shape adaptation pathways. And they generally do so in ways that protect or promote their immediate interests. The plight of actors with relatively less power is accentuated in the Anthropocene as larger risks are increasingly shifted over larger distances in space and time, rendering even actors with substantial local adaptive capacity increasingly vulnerable to disruptions beyond their immediate control. We conclude that a central, although relatively late-arriving, message of research on adaptive capacity is that efforts to understand and build it must grapple with questions of power, who has it, and how they deploy it.

The components of adaptive capacity we discuss here are akin to those identified by the research literature on general resilience; i.e., they are components that have the potential to enhance adaptive capacity for sustainability in many systems of the Anthropocene and in the face of many disturbances—even ones with which the systems have no prior experience (195). But

none of these components can be built without costs. We are left with the depressing conclusion that all must therefore be balanced, Goldilocks-like, for each specific action situation. For adaptive capacity, as for other determinants of sustainable development, there are no panaceas. In Section 8.2 on building governance capacity, we discuss what research suggests can be done about resolving these trade-offs.

Transformations: shifts from one regime and its associated development pathways to another; also called transitions (contrast with adaptation)

6. CAPACITY TO PROMOTE TRANSFORMATIONS

Transformations are shifts from one regime and its associated development pathways to another. Sustainability transformations are shifts from regimes associated with unsustainable pathways of development to alternative regimes in which development pathways are (provisionally thought to be) sustainable, e.g., from fossil to renewable energy regimes (196) or from declining to prospering fisheries (197). The need to hasten transformations of current development pathways toward sustainability is increasingly central to social and political discourse around the world (198).

6.1. Findings: Innovation, Assessment, and Incumbency

The sustainability science community has been interested in the concepts of system transformation or transition since its founding (199). The two terms have since come to be used interchangeably and without consistent distinctions in much of the literature (200). We use transformation as a term for both in this review. Multiple programs of relevant research have been active over the past decade, most with a focus on specific resources. Examples include transformations in forest use (201), demography (202), environmental justice (203), industry (29, 204) and, more broadly, sociotechnical systems (205). We cannot cover in detail the rich findings of this research. We refer readers interested in a deeper dive into sustainability transformations to four papers that review the growth of this field and synthesize results (38, 206–208). We draw heavily on these reviews for the high-level summary provided below.

6.1.1. Transformative capacity is a necessary complement of adaptive capacity. Transformations involve shifts across regime thresholds resulting in future development pathways that are qualitatively different than they would have been if the shift had not occurred. When current regimes are unsustainable, tendencies toward path dependence and lock-in can make incremental adaptation an insufficient and even counterproductive strategy for the successful pursuit of sustainability over the long run (65, 209). A capacity for promoting qualitative transformations of regimes and their associated development pathways is thus a necessary (but not sufficient) condition for sustainable development.

6.1.2. Transformative capacity must embrace the intertwined dynamics of the Anthropocene. Recent research on transformations is struggling to move beyond its earlier focus on single resources to embrace interactions among the full range of natural and anthropogenic resources described in Section 2. Its focus is thus increasingly on transforming the intertwined, coevolutionary interactions of nature and society (210). Transformations, like adaptations, are also coming to be seen not as discrete events but rather as dynamical cascades entailing multidimensional regime shifts and associated qualitative changes in development pathways (76). The implications of this dynamic character of transformation pathways for efforts to build capacity for guiding, much less managing, them are only beginning to be explored (211). Especially underexplored are the dynamics of transformations in developing countries where issues of informality and inequality are among the defining challenges (212).

Multi-level perspective (MLP): a hierarchical framework for analyzing innovation in sociotechnical systems

6.1.3. The heart of transformative capacity is innovation. The pursuit of sustainability is ultimately about finding novel ways to mobilize resources of the Anthropocene System to create inclusive well-being (167, 213). Not surprisingly, concerns for stimulating and managing appropriate innovation have therefore been at the center of many of the formative documents of the field. These have highlighted the importance of innovations not only in science and technology (214) but also in institutions and in social goals for sustainability (215). The difficulties of stimulating innovations to promote sustainability have been explored at length, particularly those due to the public good character of many of those that are most needed (216). Long missing from sustainability science, however, was either empirical case studies or conceptual models to help understand and promote the full innovation process: incentives for invention, uptake of the results, their spread and displacement of existing ways of doing things, and ultimately the transformation of practices at system scale.

This unsatisfactory state of affairs has itself been transformed through the gradual adoption into the mainstream of sustainability science of an initially independent program theorizing the history of large-scale sociotechnical transformations (38). This exciting work has demonstrated the importance of connectivity and cross-level interactions for understanding the role of novelty in general and innovation in particular in both regime stability and change. A particularly useful approach to conceptualizing the relationships between connectivity and innovation in transformation studies has been the multi-level perspective (MLP) from which the Sustainability Science Framework we presented in **Figure 1** draws inspiration (58, 208). The MLP takes as its point of departure the observation that in any given action situation, prevailing development pathways are structured by regimes (see Section 4). The positive feedbacks of the regime create path dependencies that make transformations to new development pathways difficult. Exogenous changes at higher levels of organization, such as global economic orthodoxies, wars, and climate change, put pressure on regimes that can sometimes create openings for change. But disruptions to dominant regimes are unlikely without sources of novelty. These are usually rooted in micro-levels of organization. Novelty can take many forms, including new or recombined traits of organisms, technologies, or practices; institutional structures; actors' goals, values, or behaviors; and knowledge about the Anthropocene System.

The MLP and the related literature on strategic niche management emphasize the importance of fostering diverse forms of novelty and innovations at the micro-level. The likelihood that innovations will prosper and spread is often improved by the creation of niches or protected spaces that allow for experimentation; adaptation; and the coevolution of novelty, user practices, and regulatory structures shielded from the forces of dominant regime structures (217). Managing connectivity between the micro- and meso-level is important for transforming development pathways, just as it is for adaptation. The flows of novelty from the micro- to the meso-level are influenced not only by the appropriateness of an innovation itself but also by selection rules of the relevant regime (218, 219). Actors seeking to transform development pathways must therefore attempt to change the selection relationships created by the relevant regime (220, 221).

6.1.4. Transformation must overcome path dependence. The path dependency that hinders transformation of regimes has two causes, one passive and one active. The passive cause, often cited in the literature on technological innovation, is increasing returns to scale. This is a general property of complex adaptive systems, caused by learning effects, economies of scale, adaptive expectations, and network economies (222). The active cause is action by powerful actors to block novelty that threatens the established position of winners in dominant regimes. Those actors mobilize multiple dimensions of power (see Section 4) to reinforce regimes that favor them, thus protecting their continued advantage. Indeed, powerful incumbents demonstrate a nuanced

ability not only to create barriers to expansion of novelty that threatens their interests but also to selectively influence the emergence of novelty in ways that maintain the stability of dominant regimes (223, 224). An ability to destabilize existing regimes and overcome incumbency is therefore a fundamental component of the capacity for transformation. It should thus be at the cutting edge of transformation research for sustainability.

Imaginaries: collectively held visions of good or attainable futures that serve to envision the possible and motivate action toward new development pathways

6.2. Building Capacity: Anticipation, Imagination, and Integration

The capacities for adaptation and transformation are not unrelated. But two challenges for building transformation capacity merit special attention: promoting collective visions of what sustainability transformations of the Anthropocene System might look like and combining sectoral transformations into integrated regional transformations for sustainability.

6.2.1. Transformations to what? Integrating anticipation and imagination. Transformations to what? This is a question that needs to be answered, given that the novelty and regime changes discussed earlier in this section simply send development pathways somewhere else. If that somewhere is to be toward sustainability, then transformation research needs to be self-conscious about what it is aiming for. Two approaches, recently characterized as anticipation and imagination (24), have offered partial answers. Both have strengths and weaknesses. The challenge now for sustainability science is to integrate them and thus provide better answers for its "to what" question.

Anticipatory approaches have generally started with present trends in development, sought to illuminate potentially dangerous outcomes of continuation of those trends, and explored the likely efficacy of alternative interventions designed to avoid or mitigate the dangers. Transformation research guided by such anticipatory studies is largely about shifting away from development pathways that risk being unsustainable toward a safe operating space for humanity (225). Common methods employed in anticipatory research include modeling, assessments, foresight exercises, and some forms of scenario building (226–228). Imagination-driven approaches, in contrast, have been less about what people want to avoid and more about their shared visions of what they want to achieve. Common methods do make use of science but tend to do so in a qualitative and discursive manner that can tap the arts and humanities as well. An early example is the work of the Global Scenarios Group and its successor, the Great Transition Initiative (229). More recent work is reflected in the creative use of imagination-driven scenarios in the Millennium Ecosystem Assessment and its successor, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (230).

Neither anticipation-driven nor imagination-driven approaches are pure types, and in recent years scholars have increasingly combined the two in their efforts to envision targets for sustainability transformations and plans for achieving them (e.g., 231–233). What is becoming clear in all of these approaches is the implicit conservatism of most efforts to address the "Transformation to what?" question. In particular, most efforts leave unchanged existing assumptions about relevant actors, institutions, and power structures—exactly the features that lie at the core of many worrisome development pathways (148).

The narrow framing of most efforts to envision sustainability transformations is now being questioned by scholarship emphasizing the importance of crafting more radical shared imaginaries (220). Imaginaries are collectively held visions of good or attainable futures—with an emphasis on their institutions and power relations—that serve to envision the possible and motivate action toward new development pathways (234). These in turn can stimulate new laws, regulations, and

investments in research and development of new technologies that fit the aspirations of the imagined social order (235).

What are the prospects for creating collectively held sustainability imaginaries—ones that create visions of good and attainable futures and justify investments in research and development and scale-up of more sustainable technologies and sociotechnical systems? Practitioners and activists are now leading the way on this question. For example, recent talk of a Green New Deal in many ways offers its own kind of sustainable imaginary—one that tightly couples solutions to climate change with social justice and job creation (236, 237). The challenge for sustainability science is, once again, to catch up with practice in their explorations of the question "Transformations to what?" The essence of this challenge is to build a capacity for generating answers that simultaneously make the best use of available knowledge, encourage pluralistic answers to the question for specific action situations, and create shared visions that can help to guide the collective action needed to achieve results at scale (see Section 8).

6.2.2. Integrating sectoral transformations. Combining sectoral transformations into integrated regional sustainability transformations poses an additional challenge for capacity building. When is it useful explicitly to combine work on transformations in particular sectors like energy or food into broader visions of sustainability transformations? Understanding of nexus interactions among sectors may not be sufficiently advanced to justify pushing transformation research to integrate across them. However, there is every reason to suppose that efforts to advance individual sectors in isolation will result in competition and conflict (e.g., 238, 239). Many worry that such counterproductive interactions are inevitable if the UN's multiple SDGs are pursued independently (240, 241). A way forward may be available through combining frontier work on transformations with advances in the integrated measurement of sustainable development that we reviewed in Section 3. Indeed, one possible answer to the "Transformation to what?" question would be to define a sustainability transformation as a shift from a regime in which development pathways are characterized by declining inclusive wealth to a regime in which development pathways are characterized by stable or increasing inclusive wealth. To our knowledge, this has not yet been seriously explored by sustainability science. It almost certainly should be, although with a heavy dose of humility in how far scholarship can take us in such an ultimately imaginative endeavor (242).

Building a capacity for transformation necessarily involves the creation of sustainability imaginaries and the integration of siloed sectoral approaches. Perhaps even more challenging, however, a capacity for sustainability transformation will require the ability to destabilize existing regimes that seek to preserve the unsustainable status quo (243). We defer discussion of what research can tell us about building the capacity for the collective mobilization required to destabilize dominant regimes to Section 8.2 on building governance capacity.

7. CAPACITY TO LINK KNOWLEDGE WITH ACTION

Knowledge, we argued in Section 3, is one of the key resources on which society draws to grow well-being. The stock of knowledge capital, like the stock of all resources, can be both depleted and augmented through human activities. The sustainability science community, drawing on basic research across a wide range of disciplines, has built a growing stock of knowledge over the past 20 plus years with the goal of helping to guide sustainable development. At the same time, many agitators working on the front lines of action for sustainable development continue to lament the lack of knowledge they most need. The gap between what is known or knowable about sustainable development and what is applied on the ground has long been recognized but is receiving renewed attention in the scholarly community (244–246).

7.1. Findings: Expertise, Co-Production, and Trust

We turn in this section to the body of research relevant to understanding how a capacity to link knowledge with action determines the extent to which the potential of knowledge to support informed agitation for sustainability is realized in practice. Central to that literature is the realization that knowledge is more likely to influence practice when it emerges from a dialog between experts and decision makers, rather than from one-way efforts in science communication. Who gets to participate in those dialogs—whose expertise and interests are recognized and whose are excluded—are therefore central questions that must be addressed in efforts to create trusted knowledge capable of bringing diverse and often conflictual parties together in pursuit of sustainable development goals.

Co-production: knowledge and society continually shaping each other in a dynamic, path-dependent process

7.1.1. Co-production. The most fundamental finding that research has brought to the challenge of linking knowledge with action is the idea of co-production. The essence of the idea is that knowledge and society continually reshape one another (247). What questions are (not) asked, whose evidence is (not) considered, and which sorts of explanations (do not) carry weight are shaped not just by the research community but also by society's prevailing institutions and power relationships. Reciprocally, the knowledge so produced stabilizes and legitimizes some institutions and power structures while undermining others. The resulting co-production process is a dynamic one, subject to guiding interventions but also prone to the path dependence typical of other processes in the complex Anthropocene System. Co-production, its origins as a research focus, and its implications for sustainable development are the subject of a recent critical review in this journal, the conclusions of which square largely with our own (248). We therefore refer the reader interested in the antecedents of co-production scholarship (e.g., action research, mode-2 science, post-normal science), its continuing controversies, and its current directions to that review. We focus here on the specific insights from co-production that inform the capacity to link knowledge with action in pursuit of sustainability.

A central preoccupation of scholarship informed by co-production is the question of who gets to participate in, and who gets excluded from, efforts to link knowledge with action. This work is at its core anti-elitist, critiquing and building alternatives to models of knowledge and action based on assumptions of single or hierarchically organized decision-makers informed by single experts or expert consensus. A principal focus has therefore been on enhancing participation and inclusiveness.

7.1.2. Sources of expertise. One objective of this effort has been to enhance available knowledge capital by tapping into multiple sources of expertise. This has involved efforts to bring together scholars to do interdisciplinary research with due attention to achieving mixes across genders, regions, and other attributes. But it has also entailed reaching beyond the community of scholars to include actors with relevant indigenous and local knowledge or knowledge gained from practice. The IPBES has been a leader in recent efforts to improve the diversity of expertise participating in assessments of nature–society interactions (249). A recent review of its efforts, accomplishments, and remaining challenges provides an excellent perspective on contemporary thinking about participation and inclusiveness in sustainability efforts more generally (250). Hurdles identified include reliance on established procedures for identifying experts, a bias toward natural science expertise, and the push toward consensus that too easily marginalizes views not of the mainstream.

7.1.3. Creating trusted knowledge. A second objective of enhancing participation and inclusiveness has been to strengthen the influence of knowledge on action by bringing

decision-makers and other stakeholders to join experts in the co-production process (251). This approach to co-production involves the collaborative creation of knowledge that users come to perceive as trustworthy and thus something they will allow to influence their decisions. Trustworthiness has been explored as a relational property of co-production in which potential users come to see knowledge products as meeting the criteria of saliency, credibility, and legitimacy (252). Available evidence suggests that at least minimum levels of performance on each criterion are necessary to achieve influence (253). A balanced approach is needed. Going to extreme lengths to assure scientific credibility through peer review may be effort wasted if sufficient attention is not given to steps that would assure practical relevance to decision-makers or political legitimacy through a fair treatment of contested positions (246).

Relevant to both diversifying sources of expertise and creating trusted knowledge is the fact that participation is almost always expensive for participants. Obvious costs are time and other scarce resources. But reputational risks (for experts) and political risks (for stakeholders) can also be important (254). The pursuit of sustainability, as we have emphasized throughout this review, is an inherently political activity conducted in the presence of strong incumbent interests and substantial power differentials among actors. Because knowledge is one dimension of power, experts seeking to inform agitation for sustainable development should know that they are players on a political field. This means that they are likely to be seen as taking sides in the political contest. It means that they should acknowledge that the incentives they face in deciding which questions to pursue with their research are likely to reflect the interests of the already rich or powerful. And it means taking responsibility for the fact that how they interact with other participants in the co-production process—particularly those representing marginalized knowledge and interests—has the potential to either undermine or strengthen those participants' own positions (255). The focus of recent co-production scholarship on participation and inclusiveness is a welcome corrective to more elitist models of linking knowledge with action. Still needed, however, is work to identify effective strategies for navigating the political context of participation and for identifying just what sort of participation is most important at each stage of dynamic efforts to link knowledge with action (248, 256).

7.2. Building Capacity: Social Learning, Boundary Work, and Decision Support

Building capacity to link knowledge with action for sustainability is a complex, multifaceted challenge. We highlight here several of the themes emphasized in recent extensive reviews of the topic (255, 257).

Suitably trained researchers can significantly enhance their capacity to link knowledge with action for sustainable development. Experts of all sorts have long been informing agitators for sustainability without special training, serving as a reminder that the importance of informal and experiential knowledge should not be underrated. On-the-job training is almost certainly how most of today's sustainability scientists have learned the substantive content, interdisciplinary skills, and political savvy that have helped them to contribute effectively to frontline action. And a growing number of courses and training programs are available (258). Nonetheless, the urgency of the sustainability challenge, together with the complex and rapidly developing character of the field as sketched in this review, suggests that better and more accessible training programs are needed (259). Many approaches are being tried around the world (260). An effort to pool lessons from these ongoing experiments would almost certainly be useful, although here as elsewhere in the pursuit of sustainability the temptation to advance panaceas should be resisted. Different curricula, competencies, and pedagogies will almost certainly be best suited for different people and contexts.

7.2.1. Social learning. Support for continuous, contextualized social learning is also an important component of capacity for linking knowledge with action for sustainability. Many concepts of social learning are in play (261). We focus on learning that occurs above the level of the individual in the sense that societies learn about the threat of global warming or the opportunities of globalization. Lessons learned at the social level are remembered through embedding in the facts, technologies, rules, and norms that are embodied in the relevant system's knowledge capital and social capital. An ability to learn, rather than just know, is important because of the complex adaptive character of the Anthropocene System that we have emphasized throughout this review (262). The ability to do this effectively, rather than becoming stuck in ruts of old but no longer valid knowledge, is hard to master. It has been shown to benefit from mindsets that recognize the complex adaptive character of the Anthropocene, and from the creation of organizational safe spaces that encourage experimentation. Also important are the timely acknowledgment of error, an appreciation of the co-produced character of useable knowledge, and an abiding humility of researchers as we confront the tasks before us (263, 264).

Boundary work: process through which research communities organize their relations with new science, other sources of knowledge, and the worlds of action and policy-making

7.2.2. Boundary work. Building capacity to link knowledge with action for sustainability also requires investing in organizations to carry out the boundary work of connecting experts and decision-makers (253). As expected, which forms of organization work best is context dependent. There are strong suggestions in the literature, however, that the degree of political contestation involved in choosing which actions to take makes a substantial difference in the form of the advisory system most likely to mobilize knowledge effectively. One of the most demanding situations is that in which research is called upon to advise contentious transnational or global negotiations, e.g., the Intergovernmental Panel on Climate Change (IPCC). A significant body of scholarship has examined the effectiveness of various arrangements for providing scientific assessments in such situations (265). It emphasizes the tensions that arise in arrangements to secure the credibility, saliency, and legitimacy of scientific findings for multiple users who almost always have different views of what they would like the science to say. The most vibrant area of experimentation in boundary work and organizations to carry it out is almost certainly taking place at the level of regions. Once viewed as extension work in agricultural and early industrial contexts, much of this effort is now grappling more explicitly with ideas about co-production under the umbrella term of decision support. Critical assessments have been carried out of experience with decision support organizations across a range of development activities (266), but with special emphasis in the context of advice for dealing with climate change (267). Findings are generally consistent with structuring decision support as a co-production process, entraining multiple forms of expertise, and engaging in continuing dialog with decision-makers and other stakeholders (227, 268). Like all organizations, decision support efforts are prone to getting caught in ruts and captured by particular interests (be they academic disciplines or particular users), as well as simple exhaustion. If they are to guide development pathways toward sustainability over the long run, boundary organizations must themselves be learning organizations, assisted in their efforts by periodic external reviews (269).

7.2.3. Remaining hurdles. Looking ahead, the co-production research noted above implies that sustainability science researchers face especially tough hurdles in their efforts to generate knowledge that can influence development pathways toward sustainability. One reason is that because knowledge creation is so intertwined with society and its power structures, the research that is likely to be most readily funded and adopted by decision-makers is research that supports (or at least does not threaten) current development pathways. For a lot of sustainability issues, these potential entanglements may be relatively unproblematic. But the risk is real that the

knowledge most needed by marginalized groups or interests will not get produced, as exemplified by the continuing struggle for drugs to treat neglected diseases (270). An even deeper cause for concern highlighted by the co-production perspective is that when researchers persist and do create knowledge that threatens powerful interests vested in the status quo, they often induce pushback, personal attacks, or outright disinformation campaigns. Ongoing efforts to undermine research-based knowledge on the role of fossil fuels in driving the climate crisis and the role of junk food in driving the malnutrition crisis are well-known examples (271, 272). But the pervasive resistance to inconvenient truths has even darker sides that, in their more extreme forms, surface in the continuing campaigns of intimidation and murder facing local expert-activists seeking to expose illegal deforestation around the world (273). For all of these reasons, the co-production of knowledge must be at the center of efforts to build governance arrangements to support sustainable development. We delve further into these issues in Section 8.2 on building governance capacity and in our conclusion.

8. CAPACITY FOR GOVERNANCE

Governance, as we noted in Section 2.1, consists of the arrangements by which any collectivity, from the local to the global, seeks to manage its common affairs. Governance is thus about both process (who gets what say in defining what is desirable and in doing the managing) and results (whether the managing gets us where we want to go). Governance is the product of efforts by actors to either stabilize or change existing institutional structures (including norms, rules, and practices) to meet specific goals. Those actors include governments but also a variety of other public and private actors.

Some treatments of governance for sustainable development view the role of governance as primarily one of fixing market failures. That is not the approach we take here. Rather, we echo the arguments of Mazzucato and others, who see the task of governance in general as one of creating public value—in the case of sustainable development, value denominated as inclusive well-being (136). Governance for sustainable development thus pays specific attention to the resources (both natural and anthropogenic) that society draws on to meet its goals. It involves all the key elements of the Anthropocene System summarized in the Framework for Research in Sustainability Science of **Figure 1**: actors, institutions, goals, and resources. Power differentials among actors mediate the relationships among those elements. Different action situations are governed by different arrangements of these elements and relationships. Interactions among action situations include interactions among their respective governance arrangements. Politically engaged agitators are necessarily the frontline change agents in the pursuit of sustainability. But research can help to inform agitation by identifying governance arrangements that strengthen the capacity of people to work together—not least in exercising the other capacities we have identified in this review—in the collective pursuit of sustainability.

A growing number of scholars are pursuing research to help build governance capacity for sustainability. That work is now being systematically advanced through a vigorous international program on Earth System Governance (24). We summarize here some of the most important findings to emerge from their research. We refer the reader interested in more extended coverage to several excellent books from a variety of perspectives (see 14, 274, 275).

8.1. Findings: Rescaling, Expanding the Tool Kit, Fit

Today's governance arrangements are the path-dependent product of efforts to solve the problems and seize the opportunities of previous centuries. That said, several trends in governance have

emerged over the past several decades that are shifting its foundations in ways that are particularly relevant for the pursuit of sustainability.

Fit: emphasizes the importance of matching governance arrangements to the characteristics of the action situation being governed

8.1.1. Rescaling of governance. The most general of these governance trends is the rescaling of governance arrangements beyond the historical focus on national governments (276). Three dimensions of this rescaling have received the greatest attention. The first involves spatial extent and hierarchical level: Governance today increasingly operates not just at single levels of organization but rather at multiple, interacting levels spanning the local through the national to the global (277). A second dimension involves actors: Governance increasingly involves not just governments but also firms and other private sector organizations, a blossoming array of nongovernmental organizations, and active participation by civil society (278–280). A third dimension has been the increasing linkage among action situations: Governance initiatives in particular places and sectors increasingly find themselves intertwined (281). These three dimensions of rescaling interact with one another. The result has been new varieties of polycentric systems in which multiple sources of partial authority interact to create multi-level governance arrangements that may or may not guide collective behavior toward shared goals. Polycentric governance has been argued to hold multiple potential advantages over more traditional monocentric arrangements (282). But empirical research shows that it, too, has its limitations (283).

8.1.2. Expanding the tool kit. Another broad trend in governance has been the expansion of the tool kit of interventions it employs. Formal rules and regulations will almost certainly remain important components of efforts to guide collective behavior toward more sustainable outcomes (284). But efforts to shape governance arrangements for sustainability are increasingly exploring complementary tools. These include generative tasks such as identifying emergent issues and pushing them on public agendas (285); behavioral nudges (286); the promotion of norms (287), including both responsibilities and rights of actors (288); and governing through goals (289). This expanded array of governance tools is increasingly being deployed in novel combinations to address the challenges of sustainable development (48, 275).

8.1.3. Rejecting panaceas, striving for fit. A further trend in governance is the growing (if still incomplete) rejection of panaceas claiming to be the one right way to guide collective behavior independent of particular action situations (290). Panaceas that have been advocated for pursuing sustainability include strong states, private ownership, market solutions, participatory management, polycentric governance, and a variety of other enthusiasms. Each of these governance arrangements has demonstrated value in particular situations and contexts. Each has also failed dramatically when applied to action situations where it does not fit. Indeed, the importance of fit has emerged as a central preoccupation of contemporary governance scholarship (291), a finding consistent with what we know about the central role of persistent heterogeneity in the Anthropocene (see Section 2). A remaining challenge is to sort out how diverse, polycentric governance arrangements can fit their interventions to the particular mixes of heterogeneous actors found in particular action situations, as well as to figure out how the resulting mix can be sufficiently integrated to be mutually supportive in guiding collective action (292)—a particularly urgent challenge given the diversity of the UN SDGs (86).

8.2. Building Capacity: Nurturing Resources, Promoting Equity, Confronting Uncertainty

The unsurprising conclusion of most scholars, and of this review, is that present governance arrangements are woefully inadequate to guide the accelerating and complex dynamics of the

Anthropocene toward more sustainable pathways of development (14). Better governance capacity is needed in general to support collective action for sustainable development. In particular, it is needed to support the five other capacities we have already discussed in this review: the capacity to measure sustainable development, to promote equity, to adapt to shocks and surprises, to transform the system onto more sustainable development pathways, and to link knowledge with action. Building and maintaining governance capacity, however, is always expensive—not least in the time and bandwidth it demands from all of the actors involved. Moreover, evidence from efforts to build and implement specific capacities often comes at the cost of ignoring the others (35, 293). The temptation to tailor-make unique governance arrangements for each of the capacities named above should therefore be resisted, and the search for multi-purpose governance arrangements should be prioritized. This will be hard, given the pitfalls of panaceas and the need for fit noted in Section 8.1. Fortunately, however, our reading of the evidence suggests that many of the same governance reforms could help strengthen multiple capacities. We have therefore structured our discussion of building governance capacity around three cross-cutting themes: nurturing resources, enhancing equity, and embracing uncertainty (294). We argue that progress on each of these governance themes would provide important support for the collective capacities society needs to build for the successful pursuit of sustainability.

8.2.1. Nurturing shared resources. A central challenge of governance for sustainable development is to guide the use of shared resources (capital assets) today down pathways that do not degrade the ability of those resources to nurture well-being elsewhere or tomorrow. The research we reviewed in Section 3 has established that the resources in question include all of those—both natural and anthropogenic—that form the productive base on which society relies for the goods and services that are the constituents of well-being. Scholarship on enhancing governance capacity for sustainability has focused on two dimensions of this challenge: preventing overconsumption of shared natural resources and preventing underproduction of shared anthropogenic resources.

Devising governance arrangements to avoid tragedies of the commons—overconsumption of natural resources to the detriment of social well-being—has always been a central concern for sustainable development and continues to be an area of active scholarship (295). The most extensive contribution of scholarship to this challenge has been that of Elinor Ostrom and her colleagues on common pool resources (37). Their vigorous, diverse, multidisciplinary research program has demolished the claim that only central direction by an all-powerful state can provide such governance. In its place, research has identified conditions under which and ways in which self-interested actors can work together to achieve common goals for the sustainable use of natural resources (81, 296). The core finding is the importance of arrangements that build trust among actors, encourage reciprocity in what is asked of them, and facilitate communication among them (297). These arrangements interact: A failure of one can lead to a failure of all and the consequent degradation of the resource system. Finally, the general trend toward polycentric governance arrangements we noted earlier also turns out to be a useful strategy for the particular case of collective action to manage natural resource commons (298–300). Difficulties, of course, remain (301). The highest profile of these involve questions regarding the extent to which governance arrangements that have been shown to work for managing local commons can be applied at higher organizational levels, e.g., to regional or even global problems. Researchers and practitioners have made substantial headway in advancing such a polycentric approach to create governance arrangements for nurturing larger-scale natural resource commons (e.g., 302, 303). These arrangements currently include patchworks making use of the entire expanding tool kit of governance instruments we noted earlier. A substantial body of research evaluating the determinants of effectiveness for these varied governance arrangements has also begun to emerge (304–306). This research shows clearly

that progress has been made. But shortfalls persist, and outright governance failures remain the rule rather than the exception.

Governance arrangements for sustainability are also needed because individual actors underproduce certain resources that, once provided, would enhance overall social well-being. The resources in question are potentially all of those included in the anthropogenic component of the productive base characterized in Section 3, i.e., those involved in the production of publicly accessible security and social insurance, physical infrastructure, education, health services, knowledge, technological innovation, and various forms of social capital. The character of such resources and the challenges of governance arrangements to provide them have been well-studied under the general heading of public sector economics and public goods for development (e.g., 307). Sustainability researchers have been slow to acknowledge that governance arrangements to encourage production of such anthropogenic resources can ultimately be as important for advancing sustainable development as are arrangements to discourage the overuse of natural resource commons. That is now beginning to change, with focused analysis on governance arrangements for promoting the innovations most needed for sustainable development (214), including prizes (308) and other financing measures (309). A second approach has been through analysis of what forms of treaties and other cooperative agreements have been effective in advancing the production of neglected anthropogenic resources (310). In general, the merits of the polycentric approaches and attention to local fit we noted earlier as general trends in governance have turned out to be especially important for nurturing underproduced resources for sustainable development (311).

Logics of appropriateness: the idea that action is often driven by norms of behavior rather than by rules and regulations alone; asks "what does a person such as I do in a situation such as this?"

Looking forward, numerous opportunities exist for research that would almost certainly be useful in improving the governance of resources for sustainability:

- creating more and better databases that capture the relevant governance arrangements that are actually in place around the world and how they are actually doing at nurturing resources for the pursuit of sustainability (e.g., 310, 312);
- further operationalizing the inclusive wealth metrics of resource stocks we discussed in Section 3 to provide objective functions for the design of integrative governance arrangements in lieu of those that focus only on individual sectors and resources (e.g., 112); and
- encouraging network analysis (63, 313) and complex adaptive systems modeling (80, 296) approaches for use in evaluating proposed governance arrangements.

8.2.2. Promoting equity. We noted in Section 4 that conserving the resource base is not the same as assuring equity in the distribution of the goods and services that flow from it. There is a voluminous scholarly literature relevant to governance arrangements for advancing equity, e.g., on human rights, social security, and environmental justice. We do not address that literature here. Unfortunately, the general scarcity of research on equity in sustainability that we noted in Section 4 is reflected in a scarcity of research on governance arrangements to promote the specific dimensions of equity most central to the pursuit of sustainability. Practice is therefore often ahead of scholarship in this area, with researchers mostly cataloging and analyzing governance arrangements to promote equity that frontline change agents are inventing and implementing. We summarize here some highlights of their findings.

Virtually every tool in the expanded kit of governance interventions that we summarized earlier in this section has been deployed by agitators pursuing equity in sustainable development. Scholarship is beginning to catch up. Values supporting intra- and intergenerational equity for sustainable development are being spread through a variety of mechanisms (314), with the importance of empathy (315) and efforts to enhance it (316) receiving particular attention. A value-behavior gap nonetheless persists here as in other fields (317). Norm-building efforts grounded in new logics

of appropriateness are enhancing governance capacity to guide international action in the pursuit of intragenerational equity for sustainable development (287, 318), emulating their modest success in other issue areas, such as human rights (319) and access to medicines (320). The logics of appropriateness are also behind a growing number of goals-based governance initiatives through which local governments and private firms have declared their intentions to reduce emissions of greenhouse gases that pose inequities for future generations (280). These commitments are almost certainly a good thing. But the challenges of cheap talk or greenwashing remains (321), and the efficacy of these declarations has yet to be assessed.

Novel state-backed arrangements to enhance governance capacity to promote equity are also being explored (322). Internationally, the Paris Climate Change Agreement represents a significant evolution in approaches to governance agreements for promoting intergenerational equity accords, but its durability remains to be seen (323). Nationally, sovereign wealth funds have been introduced around the world as a means for protecting the value of natural resources for future use (46). Experiments in the state appointment of public guardians for future generations are increasingly being undertaken, and their impacts are beginning to be analyzed (324). The legal arena is the site of some of the most exciting developments in both theory and practice to empower future generations, with a resurgent interest in creative application to climate change issues of the public trust doctrine, which argues that governments have a legal duty to hold certain natural resources in trust on behalf of present and future citizens (325, 326). Other proposed mechanisms for empowering future generations include mandating discount rates for calculating the benefits of climate change policies that place greater weight on the well-being of future generations, designing and embedding strategic foresight capabilities into governance bodies, and insulating decision-making from short-term political pressure (157). Rigorous evaluation of the effectiveness of these measures is, unsurprisingly, not yet available.

Social movements and political mobilization are important components of enhanced governance capacity to promote equity because of the mutually reinforcing relationship between inequity and maldistributions of power discussed in Section 4 (148, 327). Social movements are "sustained and organized collective action to effect change in institutions by citizens. . .who are excluded from routine decision-making" (328, p. 281). Social movements work by spreading the values forged in communities of micro-level activists and agitators to the institutions, including the rules, norms, values, and beliefs that undergird incumbent regimes. Successful strategies for such mobilization usually involve enhanced citizen participation and other forms of collective resistance (126, 329, 330). These are often bottom-up affairs, as is perhaps most evident in the growing global youth climate movement that consistently highlights the unfairness of present development pathways to the children and grandchildren of today's leaders in business and government (331). Recent work, however, questions blanket calls for participation that comes at significant cost to participants in terms of energy, effort, and time (332). So although promoting participation and other forms of mobilization almost certainly should remain one strategy for building governance capacity to promote equity, care must be taken that it is deployed efficiently (151, 256) and that it resists government attempts to use nominal participation as symbolic cover for continued business as usual (333).

Researchers have multiple opportunities to contribute to the enhancement of governance capacity to promote equity in sustainable development (334). Among the most important are the following:

- articulating equity or fairness as a multidimensional construct but pushing for mutual recognition of a limited range of scientifically credible and politically legitimate norm interpretations (335),

- producing and highlighting equality metrics in the valuation of current development pathways and the evaluation of possible sustainability interventions (see Section 3), and
- conducting comparative research on the effectiveness of various kinds of social movements and institutional arrangements for promoting equity in pursuit of sustainable development over long historical periods and across different kinds of action situations.

8.2.3. Confronting uncertainty. The Anthropocene is characterized by deep uncertainty, posing extraordinary challenges to governance (172). Research has made several modest contributions to clarifying the challenges and providing some guidance on what would constitute better governance capacity to address it. Here are some of the highlights.

Scholars have certainly made significant advances in understanding and modeling uncertainty in the Anthropocene System using a variety of methods that take seriously the complex and adaptive dynamics of the Anthropocene (80, 226, 296, 336–338). Despite these advances, sustainability science still has only a modest ability to predict future shocks and surprises, let alone recommend optimal development pathways over the multi-generational timescales relevant to sustainability (275). Moreover, such predictions are not in the offing. Public disclosure of asset risks (339), widespread provision of asset insurance (340, 341), and precautionary policies (342) more generally can help, but their utility remains limited in the face of deep uncertainty. This is the fundamental reason behind our focus in this review on capacities for continuing guidance rather than on recommendations for one-time decisions or hard-wired strategies.

Capacities for adaptation (Section 5) and transformation (Section 6) are essential for the pursuit of sustainability in the face of deep uncertainty. These two capacities may often compete with or undermine one another for reasons we discussed in Section 6 (35, 293). And various actors may have self-interested reasons for advancing or opposing one approach or the other (343–345). Governance capacity is therefore needed to articulate and advance the public interest in adaptation and transformation as responses to uncertainty and help balance trade-offs among them. Sustainability science to date has conducted limited research on what such governance capacity might look like (e.g., 346). The good news is that insights from studies of flexibility in systems design (347) and of real options theory by management and operations scholars (348) are applicable to this challenge. Firms routinely face strategic trade-offs between exploiting their core competencies and investing in innovation to reconfigure their assets to exploit new opportunities and respond to threats. Indeed, the actors within a single firm who work on these separate issues often find themselves in conflict and competition with one another. To manage these competing visions, best practice suggests that senior management should assign these roles to separate teams within the organization. Senior management's role is then to dispassionately weigh the evidence for and against stability and innovation and to develop a shared vision in the best interest of the overall organization (349, 350). Efforts to balance adaptation and transformation for sustainability will likely require this kind of capacity for high-level strategic thinking. At the international level, this is one of the key roles envisioned for the UN's High-Level Political Forum on Sustainable Development. Whether and how the Forum might accomplish this remain to be seen (351). And what analogous capacities would look like at other levels of governance is just beginning to be addressed by scholars.

Narratives and imagination are the focus of a second group of research results relevant to building governance capacity to pursue sustainability in the face of great uncertainty. We argued in Section 6 that actors' behavior and decisions, especially with respect to choices about the future, are motivated less by accurate anticipations of the future than by collectively held narratives (235). Current governance arrangements for sustainability have become increasingly proficient in conducting anticipatory assessments. But it is not clear that the dominant governance arrangements currently in place are particularly good at imagining more sustainable futures or embedding those

futures into collectively held imaginaries with the ability to drive change. Governance capacity to support the crafting of narratives to help guide transformations toward sustainable development pathways remains at the fringes of sustainability efforts (352).

Reflexive governance: governance arrangements that promote the ability to question one's own core commitments

A capacity for reflexive governance is the ultimate requirement that research suggests is necessary for pursuing sustainability in the face of deep uncertainty. That is, governance must be able to question its own core commitments—to evaluate whether the governance arrangements in use are part of the solution or, as is too often the case, part of the problem that just helps to confine development pathways to unsustainable trajectories (14). This is a particular case of lessons offered by the history of development in the twentieth century: Governance systems must learn to live with uncertainty rather than trying to manage or avoid it through tools of optimization and control (353, 354). Research shows that reflexive governance arrangements benefit from tools of participation and deliberative democracy that engage diverse viewpoints to widen frames, raise concerns about distribution and vulnerability, and ensure continual learning (333). A capacity for reflexive governance means balancing the flexibility for change with the stability and foresight capable of balancing the interests of current and future generations and governing sustainability over the long term. Participatory governance strategies are more likely to successfully balance flexibility and stability when they engage publics early and often (355), but no single model of reflexive governance will work in all action situations. Rather, efforts in sustainability science should strive to design governance capacity that is "flexible enough to respond to feedback from public deliberation and changing environmental conditions, while stable enough to provide a framework for collective, large-scale responses to risks" (14, p. 152). There are, once again, no panaceas. Reflexive governance arrangements will require a "fit" between these general insights and the specific conditions of particular action situations (275).

9. CONCLUSIONS

We began this review with the goal of surveying the insights that scholars have brought to bear on the challenge of sustainable development over the past 20 years. We found a rapidly emerging field of sustainability science that nonetheless remains less than the sum of its diverse parts. We concluded (to paraphrase literary theorist Northrop Frye's observations on a comparably siloed field of scholarship) that there is no reason why the greater project to which numerous individual research programs are contributing should remain forever invisible to them, "as the coral atoll is invisible to the polyp" (356, p. 12). We therefore attempted to fashion a synoptic perspective from which scholars can more readily see the remarkable progress in scientific understanding of sustainable development that is emerging from the work of the many efforts contributing to the field. The purpose of this synoptic perspective, distilled in the integrative Framework for Research in Sustainability Science presented in Section 2, is not to suggest some grand theory of the field: We remain middle-range theorists to the core. Rather, it is to highlight the union set of elements and relationships that various research approaches have shown to be especially useful in explaining nature–society interactions in particular contexts, and that therefore merit serious consideration in the formulation of future sustainability research.

From the synoptic perspective we have fashioned here, it is clear that multiple lines of research now support the long-held intuition that the Anthropocene is at its core a complex adaptive system centered in the intertwined, coevolving interactions of nature and society. Because that system is complex, it will surprise us. Because it is adaptive, innovation and other sources of novelty will drive it, making how it works tomorrow different from how it worked yesterday. Because it is heterogeneous, experience in one location will be an important but perilous guide to action in another. And because the actors who inhabit the system have their own agency and goals, power struggles will play central roles in shaping its pathways of development.

Given these properties of the Anthropocene System, sustainability science has a substantial ability to understand, but a limited ability to predict, how development pathways will actually unfold, or how particular interventions meant to guide those pathways toward sustainability will actually work out. The effective pursuit of sustainability therefore requires that researchers partner with frontline agitators to learn by doing. To be sure, this means working collaboratively to design interventions (technologies, policies, visions) that are as smart and research-informed as possible. But it also means treating those interventions as experiments, being flexible enough to revise them as more information becomes available, and mustering the courage to quickly abandon them when they do not work out as planned.

Fostering such a social learning approach to the pursuit of sustainability requires numerous operational capacities. This review highlighted research on six such capacities: the capacity to measure sustainable development, the capacity to promote equity, the capacity to support adaption, the capacity to foster transformations, the capacity to link knowledge with action, and the capacity to devise governance arrangements that allow people to work together in exercising the other capacities (see **Figure 2**). The evidence reviewed here suggests that significant progress in building these six capacities is necessary for the successful pursuit of sustainability. This capacity building, however, needs to move beyond its own siloes. The capacities we have highlighted often appear to interact with one another as potential complements (e.g., the capacity for promoting equity will be stronger if it is backed by better capacity for measuring equity). Capacities can also, however, exist in tension with one another (e.g., actors wedded to adaptation strategies may well overlook or

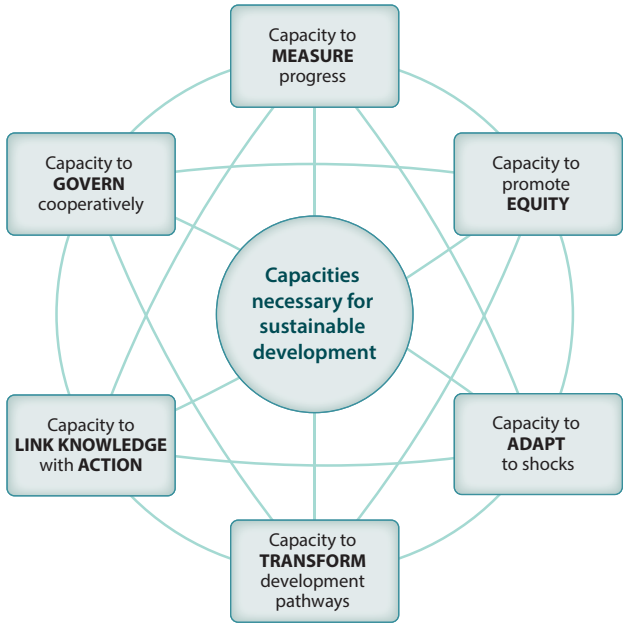


Figure 2

Capacities for sustainable development. Six interdependent capacities are necessary for the successful pursuit of sustainability: (*a*) capacity to measure progress toward sustainable development, (*b*) capacity to promote equity within and between generations, (*c*) capacity to adapt to shocks and surprises, (*d*) capacity to transform the system onto more sustainable development pathways, (*e*) capacity to link knowledge with action for sustainability, and (*f*) capacity to devise governance arrangements that allow people to work together in exercising the other capacities.

dismiss the need for transformation). Research that informs our understanding of how to build and implement the necessary capacities in an integrated fashion would go a long way toward making sustainability science more than the sum of its parts.

The practical advantage of the capacities perspective outlined here is that society has already built a significant understanding of how to foster such capacities. They can therefore be implemented today by frontline agitators pursuing sustainability at levels from the local to the global and across multiple contexts and action situations. Further strengthening and integrating these capacities should almost certainly be a high priority for sustainability science research going forward. That said, the past 20 years of research provide ample evidence that we ought to proceed humbly and reflexively not only as scholars but also as inhabitants of the complex, ever-changing Anthropocene System that we are seeking to understand. New surprises surely await, and additional capacities not yet identified will doubtless prove to be important in our collective efforts to inform agitation for the successful pursuit of sustainability.

One such surprise enveloped the world as we were finalizing this review: the SARS-CoV-2 pandemic. Like everyone else, we watched the virus kill family members and colleagues, disrupt development pathways, and trigger cascades of assaults on human well-being. The full implications of SARS-CoV-2 for sustainable development will take years to fully comprehend. Already clear, however, is that contemporary development pathways with their growing inequalities have exacerbated both the spread and the impacts of the virus. Viewed through the lens of sustainability science, SARS-CoV-2 is an all-encompassing disruption posing substantial challenges for humanity's capacities to promote inclusive well-being. That said, this pandemic, like others the world has weathered, will one day be over. When it is, we will continue to face unsustainable development pathways, held in place by path-dependent regimes and powerful, self-interested actors. Promoting transformations toward more sustainable development pathways will remain the defining challenge of our time.

SUMMARY POINTS

1. The goals of sustainable development have been debated through a multi-decade deliberative process spanning the globe. The particular constituents of the goals that are given the most weight vary across groups, places, and times. But a widely shared common vision has emerged focused on equitable improvements in human well-being within and across generations.
2. The ultimate foundations or determinants of sustainable development are the suite of natural and anthropogenic resources on which people draw to produce the goods and services that are consumed to create well-being. Development paths that deplete the ability of the resource base to generate well-being are not sustainable.
3. Interactions between nature and society in the Anthropocene constitute a globally interconnected, complex adaptive system in which heterogeneity, nonlinear relationships, innovation, and power play formative roles.
4. The complex adaptive dynamics of the Anthropocene give rise to a system that is inherently unpredictable and subject to deep uncertainty. Decisive collective action is nonetheless essential to confront the sustainability crisis. Needed are strong, polycentric, and reflexive strategies capable of advancing collaborative action agendas at all scales of social organization, even while continuously reexamining their own core commitments.

5. Such strategies for the pursuit of sustainability can be strengthened by fostering a set of six essential capacities: (*a*) the capacity to measure sustainable development, (*b*) the capacity to promote equity, (*c*) the capacity to adapt to shocks and surprises, (*d*) the capacity to transform the system onto more sustainable development pathways, (*e*) the capacity to link knowledge with action, and (*f*) the capacity to devise governance arrangements that allow people to work together in exercising the other capacities.
6. The advantage of focusing sustainability efforts on the six capacities identified here is that society has already built a significant understanding of how to foster each of them. Even as we conduct further research and experimentation to strengthen and integrate these six capacities, they can be put into action today by diverse actors across levels and between action situations to support the pursuit of a more just and sustainable world.

FUTURE ISSUES

1. As sustainability science matures as a field, it would benefit from expanding its historical emphasis on short-term, local impacts of development on environment to focus more on the long-term, large-scale patterns in the coevolution of nature and society that ultimately shape the prospects for sustainability.
2. Efforts to explain patterns in the coevolution of nature and society should embrace the finding that the Anthropocene is a complex adaptive system, and thus systematically assess the roles played by heterogeneity, multi-level organization, partial connections, innovation, and power. This also means accepting that far-from-equilibrium behavior will be the norm for the Anthropocene and that the successful pursuit of sustainability will require research to strengthen the multiple capacities needed for society to continuously learn and adjust as it navigates its pathways of development.
3. First among those capacities is better ability to evaluate the likelihood that present trajectories and proposed interventions will promote human well-being over the long run. Especially important will be extending existing metrics so that they can better integrate the contributions of all relevant resources (natural and anthropogenic), capture intra- and intergenerational equity concerns, address connections within and across levels of systems organization, and monitor the adequacy of the other capacities identified in this review.
4. The basic elements that can contribute to adaptive capacity in complex systems have been identified, but trade-offs among those elements remain poorly understood. Research is needed that illuminates strategies and guidelines for balancing such trade-offs in particular contexts and shows how to rebalance them as adaptation pathways become entwined in long-term system dynamics.
5. Transforming unsustainable pathways of development into sustainable ones is perhaps the grand challenge of sustainability science. Meeting that challenge will require above all a greater capacity to foster innovation, but also a capacity to shape the collective visions of sustainable futures needed to encourage the sorts of innovations most needed to promote sustainability.

6. Good governance—the capacity to work together in achieving what we cannot do alone—is essential for sustainable development but is always an experiment. Sustainability science needs to do better at treating it that way, documenting the governance arrangements relevant to sustainability that are in place around the world, evaluating their impacts and interactions with one another, and designing better ones—all as part of a continuing exercise in reflexive learning.
7. The asymmetric distribution of power among stakeholders in development has profound but understudied implications for sustainability. Especially needed are more creative designs of governance arrangements aimed at mitigating the intra- and intergenerational inequities in well-being that are both the cause and consequence of power asymmetries, together with systematic evaluations of the efficacy of those arrangements when they are put into practice.
8. Because knowledge itself is power, efforts to mobilize it for sustainability are inescapably intertwined with politics. The sustainability science community must therefore work actively to assure that its agenda reflects not just the interests of those who are doing well from current development pathways and thus have the money and influence to support our research, but also the interests of those who are losing out and most need our support.

DISCLOSURE STATEMENT

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