Sustainability Science: Towards a Synthesis

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Sustainability Science: Towards a Synthesis

William C. Clark and Alicia G. Harley[1]

Abstract

We review recent scholarship relevant to the pursuit of sustainable development. We find a compelling argument that the interactions of nature and society in the Anthropocene constitute a globally interconnected, complex adaptive system in which heterogeneity, nonlinear relationships, and innovation play formative roles. The dynamics of this system cannot be fully predicted but can be partially guided through appropriate interventions. We synthesize the diverse research approaches that have been applied to sustainable development challenges and construct an integrative framework that highlights elements and relationships they have found to be important for understanding the Anthropocene System. From this integrative perspective we identify six capacities that research suggests are necessary to foster sustainable development. The capacities are: i) the capacity to measure sustainable development; ii) the capacity to promote equity; iii) the capacity to adapt to shocks and surprises; iv) the capacity to transform the system onto more sustainable development pathways; v) the capacity to link knowledge with action; and vi) the capacity to devise governance arrangements that support collective action to nurture shared resources, promote equity, and confront uncertainty in pursuit of sustainability.

Keywords: sustainability science; sustainable development; Anthropocene; well-being; inclusive wealth; adaption; sustainability transformations; governance

[1]Both authors contributed equally to this work.

Contents

1 SCOPE OF THE REVIEW

We present here a strategic perspective on the central findings and current challenges of sustainability science. The field has grown dramatically since it emerged as a unified whole in the early years of this century (Bettencourt and Kaur 2011). Other reviews, many of which we cite here, have assessed in detail the research on particular parts of the field. Our goal here is to complement those focused assessments with a broader mapping of the overall contours of today's sustainability science. 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: in its case, the problem of sustainable development (Kates 2011). 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 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 (World Commission on Environment and Development 1987).

The Commission's work was a response to tensions implicit in the existence of 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 face of what many are now calling the "**Anthropocene System**[a]."[2] The first has been described by Angus Deaton as *The Great Escape* (Deaton 2013). For the vast majority of people over almost all of history life had not changed appreciably from one generation to the next. But in the late 19th and early 20th centuries, societies began to break free of earlier development constraints. Rapid improvements in health, knowledge, and material well-being spread around the world, especially in the second half of the 20th century. Today, more than 80% of the people on earth have life expectancies that are higher than those of people in the richest parts of the world as recently as 1950. The fraction living in absolute poverty has never been lower. The great escape has certainly left some people and regions behind, resulting in substantial inequalities (UNDP 2019).

[2] The term "**Anthropocene System**" has become increasingly popular across multiple research traditions under the umbrella of sustainability science. Other terms to capture the object of study in sustainability science are also in use, for example "Earth System," "World System," and various hyphenated systems. Each has its merits, and its baggage. We share the views of the Anthropocene Working Group that the Anthropocene denotes a time in which human "activities have permanently altered life on Earth, and … have left physical, chemical, and biological traces that will persist far into the geological future" (Wing and Members of the Anthropocene Working Group 2019). The Anthropocene System is thus an appropriate term to capture the accelerating global intertwining of nature and society that underlie that alteration. We adopt it here as serving better than its competitors in capturing the motivating concerns of sustainability science without privileging narrower disciplinary perspectives.

By almost any metric, however, human well-being on earth has never been higher (Roser 2019). But neither has the total human population nor its pressure on the planet's environment.

This brings us to the second global trend, characterized by John McNeill as *The Great Acceleration* (McNeill 2016). For most aspects of the environment over almost all of human history, people's impacts on nature were relatively local affairs. But since the late 19th century and, especially, since the middle of the 20th century, those impacts have become increasingly large in magnitude and global in extent. Today, no corner of the earth's environment has escaped transformation by human activities. The great acceleration has certainly entailed significant cases of environmental protection and restoration. But its overall thrust shows few signs of abating, as reflected by increasing attention to the planet's great poisoning by toxic chemicals (UN Environment 2019), the mass extinction of its biota (IPBES et al. 2019), and above all its multifaceted climate crises (IPCC 2018).

The Brundtland Commission warned that what it saw as the present course of 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? Today's development pathways are tightly bound up with dominant arrangements of states, markets, firms, and other powerful incumbents, too many of which seem so dedicated to their own self-preservation that they appear unable to sense, let alone respond to, the ubiquitous distress signals of today's Anthropocene. Indeed, many of them seek to block the innovations and rearrangements that the crisis of unsustainability demands. 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 (Dryzek and Pickering 2018). The role of science in that restructuring has been captured by Amartya Sen in his call for "**informed agitation**"[b] (Sen [2000] 2013). "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 it is so easy to waste scarce political muscle on actions that end up having little impact or, like some biofuel mandates, blunder blindly forward pushing development down even more destructive pathways.

1.2 Sustainability Science

"Sustainability science" is one convenient term for the research community's contributions to the informed agitation required to address the concerns and hopes for sustainable development articulated by the Brundtland Commission. The pool of research work potentially relevant to sustainability development is vast and rapidly expanding. We focus this review on the research about sustainable development that resides in what historian Donald Stokes has termed "Pasteur's Quadrant" (D. E. Stokes 1997): scholarship that seeks to produce generalizable guidance for use in practical problem solving. This means that we give short shrift to the essential foundations of sustainability science that are built from curiosity-driven basic research in a variety of fields ranging from ecology to economics to history (i.e., work in Stokes' "Bohr's Quadrant"). We also stop short of reviewing the application of sustainability science to solve particular problems in particular contexts, e.g., to manage irrigation systems in Nepal or to promote an energy transition in Europe (i.e., work in his "Edison's Quadrant"). Finally, in the interests of our limited space and our readers' limited time, we have forgone the temptation to

sketch a history of sustainability science. We thus omit from the citations provided here many of the founding publications of field. We concentrate instead on citing the most recent work we know that both describes current research findings and frontiers in the field and also gives credit to the earlier work on which those findings are based.

This review presents the generalizable findings made by researchers over the last two decades that we judge to be most important for informing the agitation needed to promote sustainable development. We summarize our findings here and expand upon them in the remainder of the review:

- Nature and society in the Anthropocene have become intertwined in a globally interconnected, complex adaptive system. A multiplicity of research approaches offer important if incomplete guidance for how to guide the Anthropocene toward sustainability. All too often however, these approaches fail to benefit from one another's findings. Drawing on insights from all of these approaches, we present here an integrative framework that synthesizes the elements and relationships that they have shown to be important to consider in the diagnosis of barriers to sustainability and in the evaluation of the likely outcomes of alternative actions intended to promote sustainable development (Section 2).
- Research has convincingly demonstrated that heterogeneity, nonlinearities, and innovation characterize the Anthropocene System and generate development pathways that cannot be fully predicted in advance. The implication of this inherent unpredictability is that sustainable development can realistically be pursued only through an iterative strategy that not only attends to the dynamics of the system (Section 2), but also nurtures our collective capacity to guide development pathways in a dynamic, adaptive, and reflexive manner. Research to date points to six such capacities, each of which seems likely to be necessary though not sufficient to promote sustainable development:
    - the capacity to measure sustainable development (Section 3);
    - the capacity to promote equity in the pursuit of sustainable development (Section 4);
    - the capacity to adapt to shocks and surprises that threaten sustainable development (Section 5);
    - the capacity to transform unsustainable pathways of development (Section 6); and
    - the capacity to link knowledge with action in pursuit of sustainability (Section 7).
    - the capacity to devise governance arrangements that support collective action to nurture shared resources, promote equity, and confront uncertainty in pursuit of sustainability (Section 8).

We know that our efforts to produce a manageable overview of the state of sustainability science today have entailed the omission of 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 plan to establish an open-access web site to complement this review. It will provide 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. (Here is a provisional url from which the full site will be accessible: https://sustsci.pubpub.org/.) Feedback from readers of this review will be essential for making that web site useful and up to date.

2 INTEGRATING RESEARCH FOR THE PURSUIT OF SUSTAINABILITY

Key elements and relationships in a complex adaptive system

Sustainability science draws from a great variety of perspectives including traditional and practical knowledge, ecology and economics, engineering and medicine, political science and law, and a multitude of others. These multiple foundations 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 too often divided the field into island empires with mutually incomprehensible jargon, isolated publication venues, and idiosyncratic case studies. Our effort to read across these empires in the course of preparing the present review reminded us of an observation made by Northrop Frye in the context of literary criticism: there is no reason why the larger understanding to which these separate perspectives contribute should remain forever invisible to them, like the coral atoll to the polyp.

One path toward atoll-level perspectives has long involved the construction of **frameworks**,[c] characterized by Ostrom (Ostrom 2011) as the most general form of conceptualization in science. Frameworks simply specify checklists of the **elements**[d] (variables, components) and the relationships among those elements, that researchers have found to be useful to consider in pursuing a particular research program.[3] Sustainability science does not lack for frameworks and, indeed, often seems to offer several for each of the island empires noted above. What we found most interesting in preparing this review is the considerable convergence among these frameworks in recent years, indicating that many of the same elements and relationships are proving useful to multiple research traditions relevant to sustainable development. That said, convergence in content has not led to a convergence in terminology, which creates considerable conceptual confusion and further isolates island empires.

We have attempted as part of this review to clarify the current framework confusion in a non-arbitrary way. We began by identifying through literature reviews and citation searches the frameworks that have received the most significant use in research relevant for understanding sustainable development. Table 1 summarizes the result. (Search protocols and details of the searches are provided in the SI.) Our next step was to extract from each of these popular frameworks the specific elements and relationships they identified as the most useful guides for their research. We then combined these in a common pool constituting the union set of the elements and relationships that have proven useful in the various sciences of sustainability. Finally, we resolved terminological differences for similar concepts somewhat arbitrarily, but giving priority to terms that were relatively common, that did not unnecessarily privilege particular disciplines, and that were as unambiguous as possible (i.e., were hard to confuse with one another). The terms we have adopted are defined in the text, with many highlighted through links leading to a glossary.[4] Figure 1 summarizes in a "Framework for Sustainability Science" the resulting union set of elements and relationships that historical scholarship suggests is currently worth considering in new research projects and programs in sustainability science. We emphasize that this framework is not intended as a master plan for some grand theory of the field. Rather, we offer it as a subjective synthesis of the building blocks that past research has

[3] In this view, theories are conjectures about how to explain particular patterns in the framework's elements, while models organize data from specific contexts to help test and critique theory.
[4] The glossary is provided at the end of the paper.

shown may be useful and thus should be considered in ongoing efforts to construct and test middle-range theories (Meyfroidt et al. 2018) about how to promote sustainable development in particular contexts. We believe that adoption of a common language such as that proposed here would strengthen the field of sustainability science by facilitating integration of its various pieces and decreasing barriers for interaction across the field.

The paragraphs that follow characterize the principal elements and relationships of the Framework and the **patterns**[e] they generate. Subsequent sections of this review expand on the brief characterization given here in the course of applying the Framework to our assessment of the six capacities that research in sustainability science shows should be fostered to promote our collective ability to pursue more sustainable development pathways.

Table 1 Frameworks in wide use for researching sustainable development

Name(s)	Recent overview	Special contribution(s)
Complex adaptive systems (CAS)	(Levin et al. 2013) (Preiser et al. 2018)	Local action by heterogeneous agents, constrained by higher level structures, central role of innovation/novelty
Consumption-production systems (SCP)	(Geels et al. 2015)	Beyond control of pollution from production to joint consideration of consumption and P activities
Coupled human and natural system (CHANS);	(Hull and Liu 2018)	Reciprocal links between human and natural systems; special attention to links across space
Coupled human-environment system (CHES)	(Moran 2010)	Place-based analysis of linkages, emphasizing physical and biotic environment; actors and agency
Earth system governance	(Burch at el. 2019)	Highlights importance of institutional design, agency, and power for governing nature-society interactions. Emphasis on transitions and inequality.
IPBES conceptual framework (CF), multi-evidence base (MEB)	(Tengö et al. 2014)	Focus on biodiversity, collaborative processes for fair mobilization of multiple value, knowledge systems (scientific, indigenous, local, practical)
Livelihoods	(Scoones 2009)	Local actors' entitlements and capabilities to secure access to resources and their benefits; role of agency, power, politics, and institutions
Pathways to sustainability	(Leach, Scoones, and Stirling 2010)	Normative emphasis on poverty alleviation and social justice as defined by and for particular people and contexts; analytic emphasis on power, politics, roles of problem framing, and narratives
Resilience thinking	(Reyers et al. 2018)	Intertwined social/ecological systems as CAS displaying multiple regimes; tipping points; coping with risk, adaptive capacity
Social-environmental system	(Turner et al. 2016)	Co-production of useful knowledge by actors and analysts; boundary work; trust; power; monitoring, feedback for adaptive management
Social metabolism / Industrial ecology / green chemistry / circular economy	(Haberl et al. 2019) (Loste, Roldán, and Giner 2019) (Zimmerman et al. 2020)	Focus on use of energy and biophysical resources; special attention to flows in and out of manufactured structures; technology design; trade; SD concern with adequacy of sources and sinks
Social-environmental system	(Turner et al. 2016)	Co-production of useful knowledge by actors and analysts; boundary work; trust; power; monitoring, feedback for adaptive management
Socio-ecological system (SES)	(McGinnis and Ostrom 2014)	"Action situation" focus on how actors use resources in particular contexts, and multi-level (cross-scale) linkages
Socio-technical transitions	(Loorbach, Frantzeskaki, and Avelino 2017)	Technology change and innovation as multi-level, evolutionary processes; transitions among socio-technical regimes as whole-system, deep-structure, long term, path-dependent
Welfare, wealth, and capital assets	(Irwin, Gopalakrishnan, and Randall 2016)	Well-being across generations linked to wealth defined by access to resource stocks from nature & society; substitutability among stocks

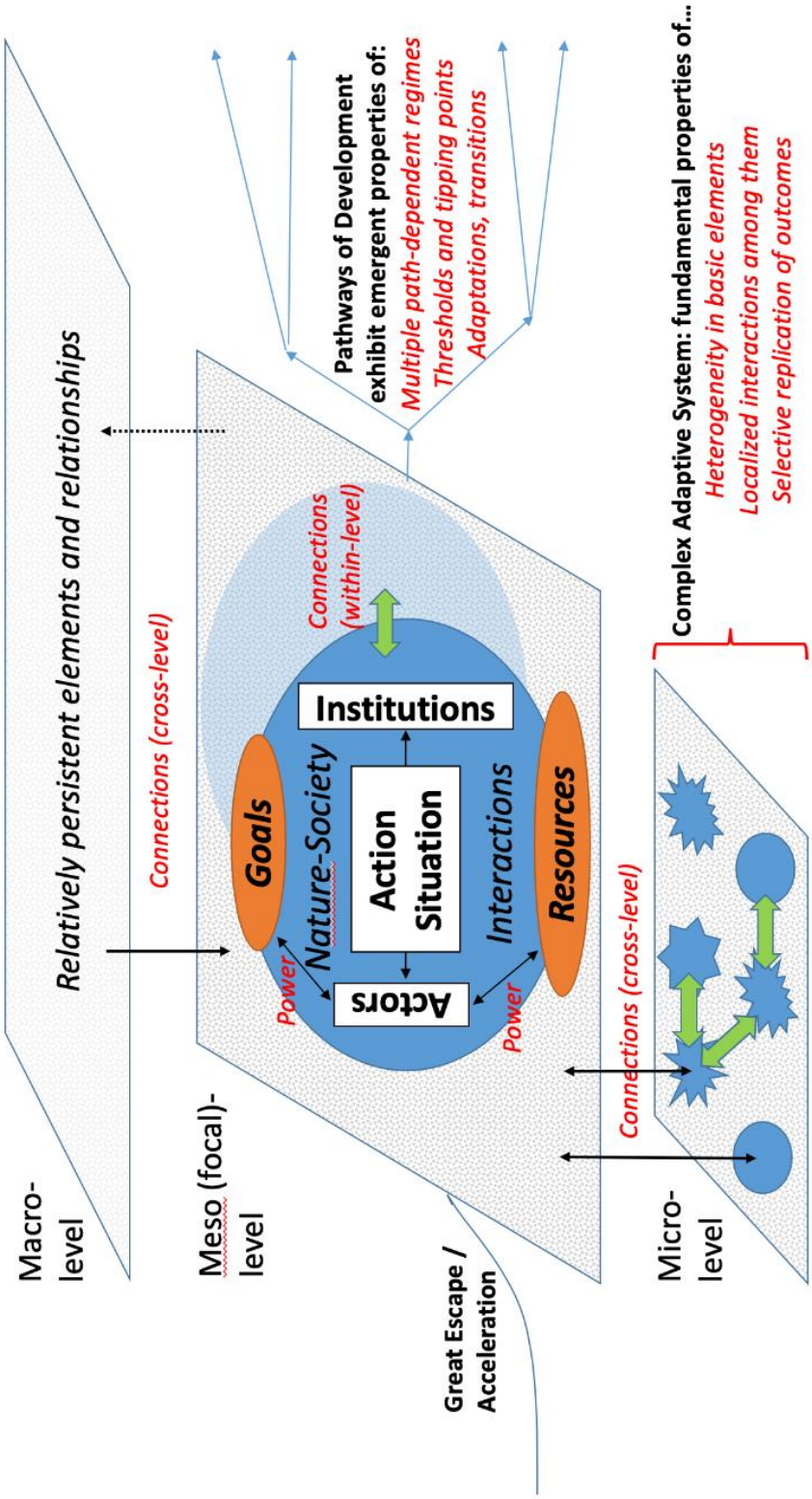

Figure 1 A Framework for Sustainability Science Research on the Anthropocene System

2.1 The Core

The core of the Framework reflects the original framing of the sustainable development challenge by the Brundtland Commission as already discussed in Section 1.

Nature-society interactions (blue)[5]: The foundation of sustainability science is research exploring what the Brundtland Commission originally termed the *inseparable* character of environment and development. Much of the early work in the field tended to focus on the dynamics of either nature or society, while treating the other as relatively constant or an exogenous forcing factor. But more recent scholarship—initially by historians and geographers and more recently by scholars of environment or technology—has shown the importance of appreciating how thoroughly these elements are intertwined in deeply co-evolutionary relationships that shape dynamical **pathways of development**[f] (Reyers et al. 2018). An immediate consequence of these findings is that talk of "social-" or "environmental-" 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 "sustainability" should always refer to the integrated pathways of development resulting from nature-society interactions in the Anthropocene System. This is the usage that we adopt throughout our review.

Goals (orange): Sustainability science is a problem-driven field. Debates on the goals of sustainable development—what they are, have been, and should be—are therefore central to the field and have occupied a core position in the Framework. The Brundtland Commission, which we quoted earlier, focused its discussion of goals on meeting human needs with special attention to intergenerational equity. Subsequent deliberations (e.g., Stiglitz, Fitoussi, and Durand 2019) have expanded Brundtland's initial attention on basic needs to encompass a broader concept of **well-being**[g] (Dietz and Jorgenson 2014). They have further emphasized the view that the alleviation of poverty today should stand side by side with a concern for the well-being of future generations in formulating sustainability goals. The United Nation's Sustainable Development Goals (SDGs) have formalized the claims of a wide range of additional interests to be accounted for in assessments of progress toward sustainability goals. The appropriate tradeoffs among such claims, both within and among generations, remain the subject of academic and political contention (Barbier and Burgess 2019; Norton 2017; Summers and Zeckhauser 2008; Zeckhauser and Viscusi 2008). The Framework pictures goals as "inside" the Anthropocene System rather than as external to it because what people want from sustainable development varies across space and time (Lintsen et al. 2018).

Resources (orange) have always been a central focus of research on sustainability. Today, the "resource" concept has broadened from early work on forests and fisheries to include multiple stocks of "capital assets" from which people draw goods and services in efforts to achieve their

[5] We prefer this framing of the interactions that shape the Anthropocene System over alternative framings that, however broad their intended meaning today, reflect in their terminology various disciplinary path-dependencies that are perceived by some as narrowing what ought to be an inclusive vocabulary. In particular, we find the connotation of "nature-society" interactions to be broader than "human-environmental" interactions (which we have found connote to many a diminution of the importance of how people organize their relationships with one another), social-ecological interactions (which connote to many a diminution of the physical aspects of nature such as climate), and "socio-technical" interactions (which connote to many a diminution of the importance of interactions with nature in the Anthropocene System).

goals. Some resource stocks considered in contemporary sustainability science are usefully thought of as "natural" in that they come principally from nature: biodiversity, ecosystems, the physical environment (e.g., climate), minerals, and other materials. Others are "anthropogenic," or made by people: 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. Questions of the tradeoffs and substitutability—especially between natural and anthropogenic resources—remains a subject of intense debate on both empirical and normative grounds (Cohen, Hepburn, and Teytelboym 2019). But one of the most important findings of sustainability science has been that natural *and* anthropogenic resources, together with the dynamic interactions between them, must be treated as the joint foundations on which inclusive human well-being can be built.

2.2 Governance

A second major component of the Framework brings questions of governance to bear on the core concepts. Governance in general can be viewed as the arrangements by which any collectivity, from the local to the global, seeks to manage its common affairs (Ruggie 2014). Governance for sustainability has been productively researched using concepts drawn from Ostrom's Institutional Analysis and Development (IAD) approach (McGinnis and Ostrom 2014). Research has identified the key dimensions of the IAD approach shown in white as well as the importance of the role of power shown in red in Figure 1 as particularly important for understanding governance of sustainable development.

Actors (white) are those elements of the Anthropocene System that have agency: the ability to articulate their own goals, influence which institutional structures are in play, and thus influence how the use of resources is governed (Betsill, Benney, and Gerlak 2020). Actors include people, households, communities, firms and other organizations, states, and comparable entities. Characteristics of actors that have long proven salient for sustainability science include their values, beliefs, interests, capabilities (including for learning and innovation), and power. More recently, a strong case has be made for the importance of actor's empathy for nature and other people in shaping pro-sustainability behaviors (Brown et al. 2019). In general, actors seeking to achieve their goals compete with one another for limited resources but may also cooperate or adopt other strategic behaviors. Some individual actors inevitably do better than others, resulting in unequal distributions of access to resources and power, and the subsequent use of power by incumbents to reinforce their advantage.

Institutions (white) are the structural dimension of governance. They constitute the rules, norms, rights, culture, and widely shared beliefs that shape the behavior of actors in their relationships with one another and with nature (Ostrom 2005). Institutions are created, reinforced and changed by actors. Much of the analytic work in sustainability science seeks to evaluate how specified changes in institutions—say, the imposition of a carbon tax—have affected or are likely to affect the prospects for achieving sustainability goals.[6]

[6] The institutional dimension of governance can also be viewed in terms of *social capital*: one of the anthropogenic resources listed in the core of this framework and explored in more detail in Section 3. We find it convenient to think of social capital as part of the stock of resources inherited by current decision makers and focus in our treatment here and in Section 8 on the options those decision makers have for changing rules, norms, and other structures of governance to alter pathways of development.

Power[h] (red arrows): Power is the ability of actors to affect the actions and beliefs of others (Hicks et al. 2016). Power can both constrain and enable choices and opportunities (Gerlak et al. 2019). Within the framework presented here, power mediates the relationships among actors, institutions, resources, and goals. Actors can either work within inherited power structures or attempt to change those structures.[7] Actors with more power can more easily change or maintain existing structures to further their power.

Action situations[i] (white) are domains or contexts of nature-society interactions in which particular actors, operating in particular institutional structures, make choices about using resources to achieve their goals. Action situations can be defined at any spatial or temporal scale, but getting the scale "right" is generally seen as essential for useful analysis and effective action (Ostrom, Janssen, and Anderies 2007). Sometimes "right" means a sectoral focus on particular production-consumption systems such as food or energy (Geels et al. 2015). Sometimes it means a place-based focus that may encompass one or multiple sectors in a particular place (Hansen and Coenen 2015). Sometimes it means an issue of concern, such as poverty alleviation or the pursuit of sustainability. For researchers, action situations are often the unit of analysis for exploring sustainability questions. For agitators, they are a choice of which functional issues to work on, and what community of other actors to work with. Recent research emphasizes that multiple action situations are always in play in the world and that outcomes of one frequently affect the challenges and opportunities facing another (Graedel and Voet 2010; Nepal et al. 2019). The resulting nexus of interacting action situations has proven extremely difficult to untangle (Galaitsi, Veysey, and Huber-Lee 2018). Figure 1 aims to capture the importance of analyzing the Anthropocene System in terms of interacting action situations by showing multiple ovals representing the core and governance elements of the system and suggesting connections among the ovals with horizontal (green) arrows.

2.3 Complexity

The third major component of the Sustainability Science Framework seeks to capture a fundamentally important finding: that the Anthropocene System is a **complex adaptive system** (CAS) [j] (Preiser et al. 2018). We build here on the work of Levin, Arrow, and colleagues who show how, and to what effect, fundamental properties of any CAS are realized in the particular case of the Anthropocene System (Levin et al. 2013; Arrow, Ehrlich, and Levin 2014). Their relevant arguments may be summarized as follows:

Three fundamental attributes of the Anthropocene make it a complex adaptive system (Levin 2003):

- The **individuality**[k] or diversity of its actors and other elements means that their behavior cannot be understood in terms of averages: Finland and Vietnam are significantly different than an average nation; carbon and mercury behave differently than a generic

[7] The tension between early scholarship in sustainability science which modeled human behavior as essentially constrained by the rules of the system, and later scholarship which endowed human agents with the capacity to change the rules of the game, mirrors larger debates in the social sciences on the primacy of structure versus agency in social systems (Archer 2003). Today, the debate over the primacy of structure or agency has more or less concluded not with an either/or, but with a yes/and where human agency often serves to recreate and stabilize existing social structures, but where humans also have the capacity to destabilize existing power structures (Chowdhury and Turner 2006).

element with their average mass; a child and a grandparent are also different than an average person.
- Local interactions among those elements give rise to outcomes that are different than if interactions were global (think of evolution on islands, or early stages of innovation sheltered from global competition).
- An autonomous selection process enhances a subset of those actors and elements based on the outcome of the local interactions (think of the reproductive advantages of a new strain of antibiotic resistant bacteria, or the spread of a superior technological or institutional innovation).

From the perspective of sustainability science, the most important consequence of these three attributes is that the Anthropocene System continually generates novelty (biological, technological, institutional) that drives its development pathways to evolve in fundamentally unpredictable ways (Arthur 2015; Hagstrom and Levin 2017). In addition, these attributes of individuality, local interactions, and selection in the Anthropocene System give rise to several additional properties that are essential for understanding their behavior: connections, hierarchical organization, and far-from-equilibrium dynamics. We summarize results of research on these dimensions of complexity below.

Connections among individual actors and other elements of the Anthropocene System exist but are incomplete. (If connectivity were complete, the individuality of actors and other elements would vanish, and they could be treated in terms of aggregate variables as is commonly done in many forms of systems modeling.) Research therefore has to take seriously the persistent individuality 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, e.g., how production activities in one patch result in the export to other patches of some of the pollution (a negative externality) or knowledge (a positive externality) it generates. More recently, this approach has expanded to consider the reciprocal "off-shoring" aspect: how increased consumption in one country connects (via the market) to increased production (and often pollution) in another. Studies of connectivity relationships have also begun to address the propagation of disturbance and novelty through the Anthropocene System (May, Levin, and Sugihara 2008). More generally, studies of "teleconnections" among people, materials, information and places (Hull and Liu 2018), of social connectivity in actor networks (Sayles et al. 2019), and of the linkages among action situations noted earlier are generating sufficiently useful insights to suggest that similar questions should be considered in most new studies for sustainability science. The Sustainability Science Framework of Figure 1 highlights the importance of analyzing such connections with its horizontal green arrows.

Hierarchical organization of the Anthropocene System emerges naturally and inevitably from the activities and incomplete interactions among its actors and other elements. Properties at higher levels can be treated as drivers of system dynamics (Dietz 2017). But many high-level properties are **emergent**[l] in that they arise from actors' collective behaviors at lower levels but cannot be explained as a simple sum of the parts of those behaviors. These emergent properties do, however, feed back—though often relatively slowly and diffusely—on the options and constraints facing individual actors at the lower levels. (A person's overall health emerges from the interactions among individual organs but will affect those organs in turn. A traffic jam

emerges from interactions among individual cars but constrains their subsequent choices.) The (un)sustainability of a development pathway is an emergent property of all the actions undertaken by individual actors within the existing system in the context of driving forces external to the system. But unsustainable pathways are often maintained through emergent path-dependence and institutional lock-in at higher levels of the hierarchy (Seto et al. 2016). A substantial body of research has been published on how hierarchical levels in the Anthropocene System are linked through a variety of "vertical" connections[8] (Martín-López et al. 2019). Special emphasis has been given to the role of "polycentric" connections across levels and elements of governance in guiding action for sustainability, and the cross-level dynamics of innovation in sustainability transformations. We return to these themes in Section 6 and Section 7, respectively. The Sustainability Science Framework of Figure 1 highlights the importance of a hierarchical perspective on the Anthropocene System through the stippled planes labeled micro, meso, and macro levels, plus the vertical connections among those levels (black arrows).

Far-from-equilibrium dynamics are the norm, not the exception in the Anthropocene CAS. These dynamics exhibit multiple **regimes**[m], or characteristic sets of behaviors driven by a particular set of dominant relationships, feedbacks, or rules of the game.[9] 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 the development pathway. Separating neighboring regimes are **thresholds**[n] (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 (Scheffer 2009; Biggs, Peterson, and Rocha 2018; Fuenfschilling and Binz 2018).[10] 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. Finally, since multiple regimes exist in the Anthropocene System, multiple opportunities exist for interactions or interplay among them (Young 2011) and for cascading regime shifts within and across levels (Rocha et al. 2018; Steffen et al. 2018). The theory behind these nonlinear dynamics is well advanced. Empirical work shows that theoretical expectations are met in particular instances. But how often? And with what long-term consequences? Little systematic evidence exists for how frequently development pathways observed in the Anthropocene System have been substantially affected by such nonlinearities. Moreover, reliable forecasts for regime shifts and the location of boundaries they cross in particular action situations remain elusive. That said, research in sustainability science is slowly developing an ability to provide early warning signals for some potential regime shifts (Scheffer et al. 2012). And an exciting program of transformation research has begun to explore the prospects for intentionally guiding development pathways from unsustainable toward sustainable regimes (see Section 6).

[8] 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.

[9] 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 non-proliferation regime), and intertwined nature-society systems (e.g., the climate regime, world food regime). For sustainability science, this last, more inclusive sense seems most appropriate. We therefore use it throughout this review.

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

These alternative pathways of co-evolving nature-society interactions—alternative regimes and the boundaries that separate them—have emerged as one of the most rewarding units of analysis for sustainability science (e.g., Loorbach, Frantzeskaki, and Avelino 2017; Rosenbloom 2017; Leach, Scoones, and Stirling 2010). They are what the field is trying to explain and ultimately to guide in the pursuit of sustainability. Our Framework reflects the possibility that future development pathways may follow alternative path-dependent regimes, divergent at critical transition points, through the tree-like structure on the right side of Figure 1.[11]

2.4 Patterns

The Sustainability Science Framework presented here brings together multiple perspectives in sustainability science that have been developed through an iterative process that observes patterns in the Anthropocene System, proposes, critiques, and tests tentative explanations of those patterns, and then further refines both patterns and explanations. The first generation of sustainability science built on research that sought to explain patterns in various parts of the overall Anthropocene System, e.g., the rise and fall of local fisheries, the factors that keep some communities stuck in poverty traps, or the emergence of a global system of energy services and associated polluting emissions.

The elements and relationships that make up the components of the Framework came out of these research efforts. Moving forward, however, sustainability science needs to study patterns that allow it to understand and test hypotheses about the many co-evolving elements and relationships of the Framework as a whole—and to do so over intergenerational time periods relevant to the core concerns of the field. Some work has already begun to fill this gap, including multiple efforts to create collections of case studies within particular action situations organized for comparative analysis, collections of time series data on relevant variables at national level, and forecasts of possible future development pathways. However, the data necessary to evaluate and test the next generation of explanations in sustainability science will require enriched characterization of long-term patterns of development of the Anthropocene System.

Research to assemble patterns that will allow rigorous testing of theories of sustainability science is extremely demanding. Few such patterns are available today. The richest documentations tend to be for single locations and short time periods. Comparisons of places tend to be snapshots, not the long time series needed for intergenerational questions. Long-term time series data tend to be for single or a few variables and divorced from context. Those few pattern descriptions that come close to what is needed for sustainability science are mostly the products of historians (e.g., S. Beckert 2014), anthropologists (e.g., Lansing 2007), geographers (e.g., Doyle 2018), or development scholars (e.g., Agrawal 2005), many of whom carried out the research for their own purposes rather than in conscious support of the sustainability science research program or a commitment to document the full range of elements and relationships that the field now finds to be important (i.e., those listed in Table 1). That said, an increasing number of relevant patterns are beginning to be documented and used for theory testing in the sustainability science literature (e.g., Turner, Geoghegan, and Foster 2004; Schlüter et al. 2019; Rudel et al. 2020). More of this sort of work in documenting patterns is needed to support the next generation of theory generation and testing in sustainability science.

[11] We prefer the branching tree image to the more common "marble-in-a-bowl" images because the branches imply continuing evolutionary dynamics and emphasize the multiplicity of future pathways that such dynamics may entail.

2.5 From Integrating Knowledge to Fostering Capacities

Over the past several decades research has built an increasingly nuanced understanding of the complex adaptive dynamics of the Anthropocene System, as well as a growing ability not only to explain the patterns of past development pathways but also to explore future scenarios and even potential tipping points and regime shifts (Bauch et al. 2016; Steffen et al. 2018). At the same time as research has made these advances, it has also convincingly demonstrated that heterogeneity, nonlinearities and innovation are fundamental properties of the Anthropocene System and generate development pathways that cannot be fully predicted in advance (Levin et al. 2013). This fundamental uncertainty means that better frameworks, theories, and models of the Anthropocene System will never be able to assure that particular development strategies will be sustainable. Instead, using our growing analytical understanding of the Anthropocene System for the pursuit of sustainability will require complementary capacities to correct and redirect as interactions between nature and society generate unpredictable and unforeseen consequences (Chapin et al. 2010). Thus, sustainable development can realistically be pursued only through an iterative strategy that combines "thinking through" (Section 2) with "acting out" (Sections 3-8). In the rest of this review, we discuss six capacities that we believe are necessary for the pursuit of sustainable development.

3 CAPACITY TO MEASURE SUSTAINABLE DEVELOPMENT

Well-being, resources, capital assets, and inclusive wealth

One of the greatest and longest standing challenges facing sustainability science has been to design and implement methods for measuring sustainable development. The measurement challenge takes two forms (Dasgupta 2001): valuing recent pathways of development (are they sustainable?); and evaluating the likely impact of policies or other interventions on future pathways of development (do they enhance the prospects for sustainability?).

Solid answers to such questions could serve at least three complementary purposes. For advocates, good metrics could help to integrate the contributions to sustainable development of the multitude of specialist preoccupations that continue to fragment the field (e.g., the multiple UN SDGs). For skeptical or self-serving actors, good metrics could rebut the claim that sustainability is just a buzz word that can be dismissed as meaning whatever anyone wants it to mean. For decision makers at all levels, good metrics could provide motivation and guidance to adopt pro-sustainability practices.

A numbing array of metrics have been used to value and evaluate development pathways. These range from GNP to carbon emissions to the Human Development Index to the SDG metrics. Most catch something relevant to sustainability, none catch everything (Laurent 2018). They have generally failed to provide the "solid answers" noted above for several reasons. Most do not even try to address the multi-generational aspects of sustainable development, but rather focus on current conditions. Most address only one or a few of the full suite of resources and other key elements that researchers have found to be important for sustainability and that we summarized in Figure 1. Most are ad hoc rather than being built on (and benefiting from) a coherent theoretical foundation (Polasky et al. 2015).

Fortunately, one of the strongest contributions of science to sustainable development over the last two decades has been an integrative, theory-grounded, and useful set of answers to one part of this central question: measuring the long-term social value of the resource base in terms of its inclusive wealth. We summarize key findings relevant below, building from the simplest and most widely accepted parts of the answer toward the more complex and controversial (but, in our view, also more useful) ones.

3.1 Key Research Findings

We summarize here key research findings on the measurement of sustainable development.

3.1.1 Measure stocks not flows

Sustainability measures must focus on stocks rather than flows. This would seem logically obvious: if one is flying a solar-powered airplane and wondering about the sustainability of its flight path, it is ultimately more important to track the battery charge (a stock) than the air speed (a flow). Flows do matter: they reflect, after all, the goods and services that people consume in pursuit of their immediate well-being, and they can both deplete and replenish stocks. But it is only through tracking the underlying stocks that the long-term sustainability of development can be assessed (Stiglitz, Fitoussi, and Durand 2019).

3.1.2 Resources are the key stocks to measure

The stocks that must be conserved as the "battery charge" for sustainable development can usefully be seen as the resources highlighted in many of the analytic frameworks discussed in Section 2. The theory behind this view has been most extensively explored in a seminal book by Partha Dasgupta (Dasgupta 2004), building on a long tradition of work in welfare economics and the economic theory of capital. It portrays resources as the **capital assets**[o] that constitute the **productive base**[p] on which people in the Anthropocene System draw to advance their well-being.[12] Some of these resources (assets) are "natural" in that they are directly derived from nature (Barbier 2019), whereas others are "anthropogenic" or constructed by people (Díaz et al. 2015). Subdivisions of these resource categories that have provide particularly useful in sustainability science research are listed and illustrated with an oceanic fishery 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 stocks of fish and stocks of boats to prosper.[13]

[12] Dietz (Dietz 2015) provides a useful discussion of the relative merits of thinking about the determinants of well-being in terms of "resources," "capital," or "assets." We use the three terms interchangeably, but generally give primacy to "resources" because of the central position of this term in many of the research frameworks drawn on by sustainability science (see Section 2).

[13] A closely related line of scholarship argues that shared resources—both natural and anthropogenic—should be viewed as "infrastructure" that serves as a multiplying mechanism generating social value that cannot be reduced to the sum of its parts (e.g., Frischmann 2012). Integration of insights from this "infrastructure" scholarship with those emerging from the "capital assets" perspective featured in this review has made some headway through their shared interest in managing resource commons (see Section 8 and Anderies, Janssen, and Schlager 2016; Bernstein et al. 2019).

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

a) Resource group	b) Specific example of an ocean fishery	c) General list of representative stocks	d) Reviews
Natural assets			(Barbier 2019)
• Ecosystems	Fish and their food	Biota, biomass, communities	(IPBES et al. 2019)
• Environment	Ocean temperature, pH	Sunlight, wind, climate, atmosphere, water	(Ekins, Gupta, and Boileau 2019)
• Minerals	Fossil fuel for the boats	Fossil fuels, iron, sand, etc.	(OECD 2018)
Anthropogenic assets			
• Manufactured capital	Boats of the fleet	Roads, buildings, infrastructure	(Weisz, Suh, and Graedel 2015)
• Human capital	Skilled fishers	Population; its health, education, distribution	(Nordin and Rooth 2018)
• Social capital	Regulations on catch	Institutions (including rules, norms, rights, culture, networks, etc.)	(Hamilton, Helliwell, and Woolcock 2016); (National Research Council (US) et al. 2014)
• Knowledge capital	Maps of the seabed	Indigenous, practical, scientific	(C. Hess and Ostrom 2007), (C. Hess 2012)

The particular resources that are most important in a given case will always depend on context, as suggested by Column B of Table 2 and the more general examples of Column C. But a growing body of 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 (see Column D, "Reviews"). Sustainability science should build on this progress and aim to adopt integrative approaches that assess the potential contributions to sustainability of all of the basic resources categories of Table 2.

3.1.3 Resource aggregation and tradeoffs

Efforts to advance peoples' well-being generally involve tradeoffs among the resource stocks (assets) that constitute the productive base of the Anthropocene System. How much of a wetland can be justifiably drained to build a road that will allow an isolated town access to markets and medical care? How should a state divide public investment between R&D and sewage treatment plants? A central concern of sustainability science has always been whether current efforts to build up the anthropogenic assets of the productive base are so damaging the natural assets as to undermine the prospects for intergenerational well-being. Which tradeoffs are consistent with sustainable development? Systematic efforts to answer this question, grounded in both theory and empirical work, are now being advanced on a number of fronts under the general banner of "Beyond GDP" (Stiglitz, Fitoussi, and Durand 2019). The variant of these approaches that has resonated most deeply with the sustainability science community is that on "inclusive wealth," advanced in a series of works by Dasgupta, Arrow, and Polasky (Dasgupta 2014; Arrow et al. 2012; Polasky et al. 2015). Inclusive wealth aggregates measures of the potential social value

latent in the full range of resource stocks that constitute the productive base. Those measures of wealth remain estimates. And they are not the same as the well-being that can be produced from the resource stocks. But under a set of useful conditions the research cited above has demonstrated that per capita inclusive wealth should track the potential for human well-being across generations. It can thus be used as a metric of sustainable development.

How tradeoffs among the resources of Table 2 are handled in inclusive wealth theory is conceptually straightforward if operationally (very) challenging. First, stipulate an intervention in the Anthropocene System that would add to one resource but at the expense of others (e.g., building a parking lot to contribute to manufactured capital on land obtained by draining a wetland which subtracts from the natural capital of the ecosystem). Next, estimate the long-term change in the social value of the productive base (i.e., in inclusive wealth) that would be expected to result from adding to (subtracting from) the system a small unit of each resource in question while holding everything else constant (e.g., adding the value of the parking lot, but subtracting the lost value of the wetland and the ecosystem services flowing from it). Finally, compare the results. These will show the marginal tradeoff between the respective resources involved in the intervention and whether the net result of the intervention is to increase or decrease net social value (inclusive wealth) of the productive base.

The approach to tradeoffs sketched above has been termed "weak sustainability" for its apparent assumption that the resources of the productive base can be substituted for one another without limit. In contrast, "strong sustainability" advocates argued that certain resources—notably those natural resources such as biodiversity and climate—cannot be reduced below critical or threshold levels without entailing significant risks of catastrophic and irreversible damage to peoples' well-being. This school of thought has argued that the inclusive wealth approach to tradeoffs sketched above could not accommodate such thresholds or limits and should therefore be rejected as a means for analyzing sustainability. Fortunately, extensions to the early theory of inclusive wealth have now developed approaches that can accommodate most of the objections cited by the "strong sustainability" and related critiques, including set-asides of resources that society determines are "essential" and should be protected absolutely, multiple equilibrium (non-convex) system structures, and both discontinuities and uncertainties in system response to resource use (e.g., Nordhaus 2019; Irwin et al. 2016) provide a comprehensive review of the "weak" vs. "strong" debate and the extensions of inclusive wealth theory that seek to address it. Even using these conceptual advances, however, the such empirical evidence as is available suggests that the substitutability of natural capital with other forms of capital may be only low to moderate (Cohen, Hepburn, and Teytelboym 2019).

3.2 Sustainability Should Be Measured in Terms of Inclusive Wealth

Inclusive wealth theory has now advanced sufficiently to provide a conceptually coherent measure of sustainable development. The measure can be used for valuing the sustainability of recent pathways of development and for evaluating whether proposed interventions enhance the prospects for sustainability.

Sustainable development should be measured in terms of inclusive wealth. For a development trajectory to be sustainable, a necessary condition is that it conserve inclusive

wealth: 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 version of this important result is subtle and merits closer attention than we can provide here. Several recent reviews provide the details (see, e.g., Dasgupta 2014; Polasky et al. 2015; Irwin, Gopalakrishnan, and Randall 2016; Siddiqi and Collins 2017). Important features of inclusive wealth that are addressed in those reviews and that are important for sustainability science scholars to appreciate include the following:

- "Well-being" of people is the goal or end objective of sustainable development. It has multiple constituents, the importance of which will vary across people and generations.
- "Wealth" is a means to the end of social well-being. It has multiple components, natural and anthropogenic, that together constitute determinants of well-being. Wealth is not the total amount of resource. Nor is it their monetary value. Rather it is the social value of those resources as the ultimate foundations, means, or determinants for the creation of well-being.
- The "social value" of resource stocks to particular social actors depends on their goals for sustainability, in particular 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;
- "Conserving" inclusive wealth means that it 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 assets will meet the "conservation" criterion for sustainability;
- "Inclusive wealth" is always about forecasts: what value society could expect to produce from a specified endowment of resources given a particular set of assumptions about how (relevant parts of) the Anthropocene System works and which actors have the power to make it work for them (e.g., the assumptions used for an IPCC scenario);
- Estimates of inclusive wealth are only about the potential of the relevant system to produce well-being, a potential that may not be realized in practice if the assumptions of the forecasting model turn out to be wrong, or are violated (e.g., some actors cheat on an agreement that the forecast assumed would be followed) or if external shocks displace the system from the forecast development pathway.

These subtleties of inclusive wealth theory and its "Beyond GDP" relatives pose substantial challenges for both understanding and application. But practical applications have nonetheless begun to accumulate. These include a growing array of science-grounded assessments of the sustainability of recent development patterns (Tzvetkova and Hepburn 2019). These have been carried out by individual scholars (Arrow et al. 2012; Lintsen et al. 2018), by non-governmental organizations (Managi and Kumar 2018), and by the World Bank (Lange, Wodon, and Carey 2018). Moreover, the theory is beginning to be employed in prospective evaluations of alternative policies for promoting sustainability in cases ranging from massive desalinization for the production of drinking water (R. D. Collins et al. 2017) to mitigating the risk of collapse of the Greenland ice sheet (Nordhaus 2019). Much remains to be done, and the data demands for a fully inclusive estimate of wealth are daunting. But the current trajectory of research and application on inclusive wealth represents a significant advance over a past in which, Humpty-Dumpty-like, sustainability was whatever those declaiming about it wanted it to be.

3.3 Toward a Capacity for Measuring Sustainable Development

The advances noted above notwithstanding, the challenges of fully developing and operationalizing inclusive wealth as a practical measure of sustainable development remain substantial.

3.3.1 Valuing resources

A combination of methods and models are now being employed to provide useful estimates of the social value of resource stocks. Some are anchored in the social deliberation (Dryzek and Stevenson 2014), others in systems simulation (R. D. Collins et al. 2017), 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 (Yamaguchi and Managi 2019).

Science's ability to assign social value to increments of manufactured capital and mineral capital is relatively advanced (e.g., Miller et al. 2019). And great deal of overdue progress has been made more recently in valuing some other natural capitals and the services they provide to society, though estimates are still available for only a small subset of those that would be needed for a full accounting of how human activities change nature's contributions to people (Barbier 2019).[14] Human capital, in contrast, has proven surprisingly difficult to bring into inclusive wealth accounts, largely because of conceptual difficulties in how to value both population growth and changes in human survival and healthiness (Dasgupta 2019). Social capital and knowledge capital are generally acknowledged to contribute greatly, even dominantly, to well-being.[15] And they are the resources most likely to have their social value enhanced by innovation, a driving force behind the development pathways of complex adaptive systems such as the Anthropocene. But they have not been well integrated into inclusive wealth theory or measurement (see, however, National Research Council (US) et al. 2014; Siddiqi and Collins 2017).[16] Rectifying these various shortfalls in the valuation of individual resources should be a central task of future research in sustainability science. That said, the prospects for progress on each and all of these valuation challenges would be substantially advanced by the further development of models more capable of forecasting the continuing evolution of the full Anthropocene System under both "business as usual" and particular policy interventions (Lawler et al. 2014; Sterner et al. 2019; Anderies, Mathias, and Janssen 2019).

[14] Research on the "social cost of carbon" is particularly worth following as a potential model, since its focus on the degradation of environmental capital through pollution by excess carbon explicitly grapples with the long time scales, tipping points, and uncertainties central to sustainability questions (Nordhaus 2017).

[15] They are often grouped together as "intangible capital" that acts as a multiplier on the potential contributions of other more "tangible" resources. This seems an unnecessary complication: like other resources, social capital and knowledge capital can be degraded or enhanced through human action.

[16] Efforts to equate the contributions of these assets to human well-being with the role of "total factor productivity (TFP)" often used in analysis of economic growth can misleading. TFP is often estimated as the residual contribution to well-being unaccounted for by measured assets. But since we now know that much of the contribution of natural capital remains unmeasured in standard accounts, the residual labeled TFP is revealed as a (big) jumble of multiple assets and unknowns. Using it as though it were a meaningful estimate of the contribution of social and knowledge capital to well-being can only mislead.

3.3.2 Accounting for connections

Connections among heterogeneous systems units of the Anthropocene System are now generally accepted to be important determinants of system behavior and sustainability (see Figure 1). This importance clearly ought to extend to inclusive wealth accounts, since activities in one place can draw resources from, or degrade resources in, another (e.g., resource extraction by colonial regimes, trans-boundary pollution, innovation spillovers). To date, however, virtually all of the theory and empirical work on inclusive wealth ignores connections within and across levels of system organization. This shortfall seems more one of neglect than of inherent conceptual difficulty, and thus should be a ripe area for future research in efforts to develop a mature capacity to measure sustainable development.

3.3.3 Building capacity for measuring inclusive wealth in context

The science of measuring sustainable development is now sufficiently advanced that its regular application to decision making at all levels would almost certainly be useful. The capacity to carry out such applications, however, remains limited. The regular reports on sustainability measures noted above almost all are carried out on the assumption that nation states are the relevant action situation. That is a start. But other contexts are also important, including subnational levels of decision making (e.g., cities, sectors, and firms). Most of these still lack capacity to carry out the needed measurements and analysis. In addition, sustainability reporting must also take account of transboundary flows to ensure that improving measurements in one region or country are not simply a result of exporting pollution or overexploitation of resources in another. Platforms to access tools and data being development by the UN (e.g., UNECE 2019) and European Commission (e.g., European Commission 2019) point the way forward. But much more systematic capacity development will be needed for the potential contribution of recent scientific advances to be realized in practice.

3.3.4 Extending measures beyond resources

The progress on measuring sustainable development that we have summarized in this section has focused almost entirely on the base of productive resources from which people build their well-being. Measures are also needed, however, of the operational capacities addressed in the remainder of this review. Much less research has been devoted to the theory and application of such measures, though initial efforts to evaluate adaptive capacity in terms of capital assets show promise (Walker et al. 2010; Tinch et al. 2015; de Bruijn et al. 2017). Expanding research on metrics of sustainable development to encompass the full range of capacities highlighted in this review should be a priority for sustainability science.

4 CAPACITY TO PROMOTE EQUITY

Inequality, poverty, power and empowerment

Equity[q] is about justness and fairness. Equitable distribution of the fruits of the earth's resources within and between generations has long been central to discussions on the goals of sustainable development. The Brundtland Commission put equity at the core of its case for sustainability (World Commission on Environment and Development 1987, 6). Subsequent international deliberations have reaffirmed this perspective with specific emphasis on both alleviating poverty and deprivation of the poorest and most vulnerable members of society and assuring that efforts

to improve well-being today do not unfairly undermine the prospects of those seeking it tomorrow. Normative commitments to the poorest and most vulnerable (including future generations) have broadened from helping them to meet their basic needs for water, food, and housing, to increasing their freedoms and capabilities to pursue their own goals and objectives (Sen [2000] 2013).

The normative commitment to enhancing intra and intergenerational equity embedded in every widely accepted articulation of sustainable development notwithstanding, the equity dimension of sustainability has been strangely neglected in practice. One need look no further than the UN SDGs for evidence of this neglect. While the preamble to the SDGs acknowledges the importance of both "present and future generations," none of the 17 SDGs explicitly addresses intergenerational equity (Lim, Søgaard Jørgensen, and Wyborn 2018; Ribas, Lucena, and Schaeffer 2017; Scherer et al. 2018).

A second example of the neglect of equity metrics can be seen in efforts we summarized in Section 3 to operationalize the idea of inclusive wealth as a measure of sustainable development. The basic theory of inclusive wealth addresses both intra and intergenerational equity concerns through its treatment of how different individuals' access to resources should be aggregated across space and time to assess overall social wealth and well-being (Dasgupta 2001). In particular, the theory allows for different weights to be given to the resources accessible to rich and poor people, and to people in the present and future. In practice, however, neither elaborations of the theory nor its use in reporting inclusive wealth have kept these distributional issues to the fore.[17] The UN and World Bank's reports on patterns of inclusive wealth and related metrics have thus far focused on data at the national level (Lange, Wodon, and Carey 2018; Managi and Kumar 2018), through a few accounts of within country variation have begun to emerge, including some detailed Japanese studies that explicitly address inequalities within the country and across capital assets (e.g., Ikeda et al. 2017). None of these works explicitly address the implications of their metrics for the equity concerns that the Brundtland Commission so clearly placed at the center of the quest for sustainable development.

The relative neglect of equity extends, somewhat surprisingly, to the research literature in sustainability science. For example, few of the book-length treatments of sustainable development we consulted for this review had more than rudimentary entries for equity or the related terms of equality, justice, fairness, or power. And significantly fewer research papers on sustainability address equity or related issues than address any of the other capacity requirements that emerged from our review.

This neglect notwithstanding, society cannot achieve the goals of sustainable development that it has repeatedly endorsed without creating more just distributions of well-being both within and between generations. In recognition of the central but neglected position of equity in the goals of

[17] Dasgupta, for example, has argued that in theory the shadow price of property belonging to someone poor should be valued higher than the same property belonging to someone wealthy (Dasgupta 2014). However, assigning all of the resources that make up the inclusive wealth function to individuals turns out to be more difficult and controversial to do in practice (Roman and Thiry 2016). In place of intragenerational shadow prices, Dasgupta suggests that analysts should "keep inequality in the distribution of well-being among contemporaries separate from inequality across the generations and to include a separate index of inequality among contemporaries. The Gini coefficient of wealth inequality is one possibility" (Dasgupta 2014, 20).

sustainable development, we argue here that a second necessary (but not sufficient) condition for sustainable development is the capacity to promote equity within and between generations. In the remainder of this section we highlight some of the existing research that provides a foundation for that capacity building effort. In particular, we summarize research on the relationship of equity to sustainability goals; on why inequity is a persistent feature of the Anthropocene System; on the connections among power, inequity, and sustainable development; and on the prospects for creating more equitable development pathways. The following reviews provide deeper treatments of these topics than we can cover here: (Hamann et al. 2018; Zucman 2019; McGee and Pettit 2019; Scheffer et al. 2017; Kashwan, MacLean, and García-López 2019; Caney 2018; Cottier, Lalani, and Siziba 2019). We have drawn heavily on them in shaping our argument.

4.1 Equity and Sustainable Development

Scholarship on inequality, poverty, and environmental justice all have the potential to contribute to our understanding of both the normative and analytical dimensions of equity in sustainable development.

First, however, some terminological clarifications are in order. The terms (in)equity and (in)equality are often conflated and used interchangeably in discussions of sustainable development. They are, however, worth distinguishing. (In)equality can most usefully be understood in terms of quantifiable metrics of distribution: income, wealth, life expectancy, access to energy, and so on. It is most often reported using Gini coefficients or related statistics. (In)equity refers to qualities of justice and fairness in those distributions (Holden, Linnerud, and Banister 2014). Multiple inequalities—in access to resources, but also in income, race, class, gender, ethnicity, nationality and other factors—frequently intersect with and reinforce one another (P. H. Collins 2015). We focus here on (in)equity, arguing that it is a more useful property for including in the goals of sustainable development precisely because of its normativity and openness to context-dependent interpretation. Sustainable development goals are defined by almost no one to aspire to perfect equality in all dimensions. Deciding exactly how to pursue greater equity will vary across different action situations and should be part of local decision-making processes. Conceptually, it is possible to consider specific categories for which concepts of justice and fairness demand equality and other categories where equity does not demand equality. Amartya Sen points out that basic rights and liberties should almost certainly be distributed equally, whereas an effort to ensure equality of life expectancy would lead to the perverse policy goals like limiting healthcare to women in order to make their average life expectancy equal to that of men (Sen 2009). In order to advance the goals that explicitly include greater equity, it is of course necessary to measure and track quantitative data on inequality to inform our understanding of equity and to identify areas where maldistributions are particularly acute.

Scholars of inequality have documented the ways in which quantifiable metrics of income and wealth are distributed between actors in different action situations ranging in level from micro to macro (Abel and Deitz 2019; Le Galès and Pierson 2019; Milanovic 2016). They have also explored inequality over time and have described both patterns of inequality in pre-modern societies and trends in inequality over the past several decades. Their findings reveal two incongruous patterns: declining inequality among countries around the globe and increasing

inequality within many countries and regions (Keeley 2015; Milanovic 2018; Piketty 2014; Scheidel 2017; Stiglitz 2012). Researchers studying inequality have also shown durable relationships between inequality and exploitation of natural resources (Ceddia 2019) as well as feedback loops and cross-level linkages between the extent of inequality and impacts on the environment (Hamann et al. 2018).

Perhaps the most extreme form of inequity is the continued existence of poverty in a world of wealth. To be sure, the proportion of the world's population living in poverty is declining and now lower than it has been at any time in the last two centuries. And by some common metrics the same is even true of absolute numbers (see https://ourworldindata.org/ extreme-poverty). But this just makes the unfairness of the current situation all the more acute. Moreover, scholars of poverty have raised concerns that despite substantial declines in extreme poverty noted above, continued conflict in regions with high rates of extreme poverty, poor governance, and increasing costs of adaptation to the global climate crisis will make further reductions increasingly difficult to achieve (Nelson et al. 2016; Ravallion 2016; World Bank 2018).

As with inequality, research on poverty documents relationships and feedback loops between poverty and lack of access to both natural and anthropogenic resources, the goods and services derived from those resources, and reciprocal impacts on asset stocks. Research on energy poverty, for example, has shown how 1.25 to 3 billion people lack access to energy for cooking, illumination and mechanical work often forcing households to further deplete local natural capital for fuel (Guruswamy 2011). Research on poverty traps has demonstrated how locally degraded natural resources can make it extremely difficult for poor households to escape self-reinforcing development pathways that keep them in persistent poverty (Barbier and Hochard 2019; C. B. Barrett, Garg, and McBride 2016; Haider et al. 2018). Research on the psychology of poverty has shown that poverty can lead to 'aspiration failure' which causes behavioral poverty traps (Dalton, Ghosal, and Mani 2016) and that the cognitive impacts of poverty and hunger can impede decision making (Mani et al. 2013). Scholars also express increasing concern that there may be tensions between improving the well-being of the poorest and achieving climate stabilization (Ribas, Lucena, and Schaeffer 2017; Roy et al. 2018; Woodward 2015). Scholars of environmental justice have demonstrated a strong relationship between access to natural resources and social justice. They also highlight the disproportionate burden on poor and vulnerable communities of pollution and degraded environments (Agyeman et al. 2016; Cushing et al. 2015; Muller, Sampson, and Winter 2018).

Equity across generations is also central to the goals of sustainable development. The question of what responsibilities one generation has for future generations raises ethical and theoretical questions (Asheim 2010). The philosopher John Rawls argued that any discussion of what contemporaries owe one another is "incomplete" without first considering what they owe to future generations (Rawls 1971 as quoted in Caney 2018). The Brundtland Commission's set of principles for inter-generational responsibility was refined by Robert Solow as the requirement to pass on to the next generation "whatever it takes to achieve a standard of living at least as good as our own and to look after their next generation similarly" (Solow 1993, 168). Solow's re-formulation of Brundtland's sustainability principle included two important properties for turning the principle into practice. First, by focusing on living standards, he pointed toward a way of evaluating whether or not current development pathways are compromising future

generations. Second, Solow's recursive formulation of inter-generational sustainability—that each generation take care of the generation directly after it—reduced the complexities and uncertainties inherent in making polices intended to impact the distant future. Following Solow, we have argued (Section 3) that sustainable development can be evaluated by asking whether the social value of resources likely to be available to the next generation is at least equal to the value of the resources available to the present generation.

Scientific assessments (e.g., IPCC 2018) suggest that the answer to this question may well be "no," and that the current generation is thus imposing intergenerational inequities on its children and grandchildren. Yet, many of the formal frameworks or approaches used in sustainability science (see Section 2) unaccountably fail to confront directly the challenge of intergenerational responsibility (Scoones 2009). How exactly to integrate future generations into 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 (Gollier and Hammitt 2014). Practically, suitable legal and regulatory mechanisms to ensure whatever rights we grant to future generations are honored by today's decision-makers are still being developed and tested (Boston 2017).

4.2 Inequity Is an Emergent Property of the Anthropocene System

Heterogeneity has been recognized as a defining characteristic of the Anthropocene System (see Section 2 and Figure 1). Most resources of the system—natural or anthropogenic—are more likely to be distributed in some heterogeneous pattern than in a perfectly homogenous pattern. This heterogeneity in complex adaptive systems such as the Anthropocene can be expected to generate inequality in both nature and society (Scheffer et al. 2017).

Empirical evidence supports this claim, demonstrating that resources are unequally distributed within and between generations (Keys et al. 2019; Hamann et al. 2018). Moreover, research in economics and political science shows that wealth inequality tends to snowball such that without intervention unequal wealth distributions become even more unequal over time. Understanding its determinants therefore requires a multi-generational historical perspective (Scheve and Stasavage 2017). The historical record does, however, demonstrate many instances of declining inequality in response to interventions designed to promote equity as well as to major shocks and disruptions. These include micro-processes of accumulation and distribution (Benhabib and Bisin 2018), meso-level institutional structures such as inheritance taxes (Piketty and Zucman 2015), and macro-forces including wars and natural calamities (Scheidel 2017). That said, many inequity reducing mechanisms that characterized much of the 20th 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 (Lamont 2019). Current development pathways are therefore not only leading to increasing inequity but also the possibility that we have moved into a high-inequity regime, where processes of advantage and disadvantage are self-reinforcing (Grusky and MacLean 2016).

4.3 Power and Inequity

Inequalities would result from the heterogeneous distribution of resources in the Anthropocene System even if all actors preferred an equitable allocation. But all actors don't. 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 (Milfont et al. 2018) to the norms of capitalism to realist tendencies 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 influence the actions and beliefs of others.

The power of actors and the unequal distribution of power among them have long been neglected in most strands of sustainability science research, but the topic is now receiving increasing attention. The growing literature on power and empowerment is diverse, but what much of this work has in common is a recognition that access to resources (including each of the resources discussed in Section 3) is at the heart of individual power (Friedmann 1992; Kabeer 1999; Pedde et al. 2019). Inequitable resource distributions lead to maldistributions of power which in turn reduce the abilities of all but the most powerful actors in the action situation to define and pursue their own goals. The pursuit of sustainable development is thus a political agenda that requires redistribution of resources and access to the flows of benefits from those resources both within and between generations. To do this, those agitating for sustainable development will almost certainly have to overcome existing power structures by working to empower the individuals and groups that are most harmed by current development pathways including both vulnerable communities today and future generations.

Society's ability to reform institutions and re-shape markets in ways that decrease inequality and lead to more sustainable and inclusive development pathways are key concerns of some of the most innovative social science research today (Mazzucato 2018a). That research has illuminated how inequity in the Anthropocene System is shaped by the institutions that determine access to resources and the flows of goods and services from those resources. It shows that some institutional arrangements such as strong unions are more likely to promote equity (Ahlquist 2017). In contrast, tax systems can exacerbate gaps between the rich and the poor when they disproportionately tax wages over income derived from investments, ownership of intellectual property, and stocks of scarce natural resources (Stiglitz 2012). Because institutions are created, reinforced, and changed by actors (see Section 2), those with more power have greater ability to create and maintain institutional structures that benefit their interests, often at the expense of less powerful actors. For example, the ability of colonial governments to extract vast quantities of resources and labor from their colonies, promoting their own well-being at the expense of others, was predicated on maldistributions of military and economic power (Mann 2012; Milanovic, Lindert, and Williamson 2011).

Inequity 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 over-exploitation of natural resources and worrisome patterns of resource use (Barbier and Hochard 2018; Duraiappah 1998; Brisbois, Morris, and de Loë 2019). And unchecked corporate power has enabled fossil fuel interests to discredit climate science and delay action on global warming thus harming future generations (Cook et al. 2019; Leonard 2019). 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**[r]: the ways that power structures shape and stabilize existing regimes and their associated development pathways (Stirling 2019).

4.4 Prospects for Equity and Empowerment in the Anthropocene System

Thus far, this section has argued that both intra and intergenerational equity are core normative concerns for sustainable development. Moreover, many of today's unsustainable development pathways are reinforced by maldistributions of power that, together with inequity, are emergent properties of the Anthropocene System. These two arguments together suggest that empowerment of disempowered populations is an essential step in building the capacity to promote equity in the Anthropocene System. Such empowerment would help both to ensure greater intra and intergenerational equity and to limit the power of currently powerful actors to further enrich themselves at the expense of vulnerable populations in current and future generations.

Fostering the capacity to support equity within and between generations will almost certainly require social movements to overcome entrenched power structures, but it will also require new institutions (including norms, rights, regulations, and laws) to ensure that the power of social movements is back-stopped by long-term shifts toward more equitable development pathways. The importance of both social movements and institutional design for more equitable development pathways stems from the nature of power as a multi-dimensional force which mediates the relationships among actors, institutions, resources, and goals and leads to patterns of incumbency (see discussion of power in Section 2). Scholars of empowerment argue that understanding the nature of power is a prerequisite for understanding the appropriate strategies for overcoming maldistributions of power (McGee and Pettit 2019). However, the growing literature on power in sustainability science remains disjointed—failing to either build on itself or converge around a common theoretical language with which to discuss the mechanisms of power (Gerlak et al. 2019). Our review of the core political and sociological approaches to the study of power (e.g., Lukes 1974; Dahl 1957; Bachrach and Baratz 1970; Foucault 1979; Haugaard 2002) as well as contemporary approaches to power in sustainability science literature (e.g., Avelino 2017; Avelino and Wittmayer 2016; Boonstra 2016; Kashwan, Maclean, and García-López 2019; Clement 2010; Brisbois, Morris, and de Loë 2019) leads us to conclude that future work in sustainability science would be well served to build on the three-dimensional view of power first articulated by Steven Lukes (1974). We selected Lukes' 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 articulated in Section 2 and Figure 1. Lukes proposes three dimensions of power:[18]

i) ownership or access to natural and anthropogenic resources and/or flows of benefits from those resources,

ii) institutional structures that protect and promote the interests of some actors often at the expense of others, and

iii) the goals, aspirations, values, and even knowledge systems that privilege the well-being of some actors over others.

[18] Box 1 summarizes a useful language based on Lukes for the analysis of power. We believe that use of this language would help to integrate analysis of power it into sustainability science research.

Box 1: Understanding Power in Sustainability Science

In response to the increasing awareness that ***maldistributions of power*** reinforce unsustainable development pathways, there is more and more scholarship addressing power in sustainability science. However, this literature remains disjointed—failing to either build on itself or converge around a common theoretical language with which to discuss the mechanisms of power (Gerlak et al. 2019). Having reviewed core political and sociological approaches to the study of power (e.g., Lukes 1974; Dahl 1957; Bachrach and Baratz 1970; Foucault 1979; Haugaard 2002) as well as contemporary approaches to power in sustainability science literature (e.g., Avelino 2017; Avelino and Wittmayer 2016; Boonstra 2016; Kashwan, Maclean, and García-López 2019; Clement 2010) we believe that future work in sustainability science would be well served to build on the three-dimensional view of power first articulated by Steven Lukes (1974). We selected Lukes' approach both because it is one of the citations most frequently used to conceptualize the mechanisms of power in empirical work, and because by articulating power's relationship between actors, resources, institutions, and goals, the three-dimensional view of power complements the Framework for Sustainability Science.	
First dimension of power: *Compulsion*	Actor A has power over actor B to the extent that he can compel B to do something that B would not otherwise do. This dimension of power is derived from ownership of or access to natural and anthropogenic resources. The ability of colonial governments to extract vast quantities of resources and labor from others was predicated on military and economic power derived from control over resources (Mann 2012).
Second dimension of power: *Exclusion*	Actor A has power over actor B to the extent that A can exclude B from decision making arenas and restructure rules and norms to further their own interests. This dimension of power is derived from the ability to shape institutional structures including rules and norms to serve their own interest often at the expense of other actors and groups. The ability of Canadian energy interests to block collaborative governance efforts to protect local common pool resources was predicated on their ability to limit the scope of negotiations and eliminate from consideration potential outcomes that would negatively impact the interests of industry (Brisbois, Morris, and de Loë 2019).
Third dimension of power: *Influence*	Actor A has power over actor B to the extent that A can influence or shape B's aspirations and beliefs. This dimension of power is derived from the ability of actors to influence information often through the media and to influence cultural values and expectations. The third dimension of power is considered the most insidious dimension because it prevents observable conflict from arising. The ability of ExxonMobil to stymie efforts to regulate greenhouse gases was predicated on their ability influence public beliefs about the threats (or lack thereof) of climate change is predicated (Supran and Oreskes 2017).

These three dimensions of power affect many, if not all, of the elements and relationships that characterize the Anthropocene System. One of the most troubling aspects of the three dimensions of power is that the dimensions serve to reinforce one another. John Gaventa's classic study of Appalachian coal country demonstrates that when the powerful actors (in this case owners of the local coal company) lost their grip on one dimension of power, they were able to mobilize their control over the other two dimensions in order to protect their interests until they were able to reestablish control over all three dimensions (Gaventa 1980). Successful resistance was possible only when agitators strategically mobilized against all three dimensions of power through collective issue framing to identify inequities (3rd dimension of power), formulation of specific demands for changes in rules and norms (2nd dimension of power), and open protests and conflict over the resources from which the coal company drew its power (1st dimension of power).

Efforts to mobilize against all three dimensions of power can be seen in more recent struggles to promote sustainable development. Activists often lack both resources and entrée to decision-making fora. But they are able to turn to the third dimension of power in initial efforts to fight unsustainable but incumbent regimes. The power of persuasion can be seen in the efforts of young people around the world to influence global leaders to act on climate change. Similar uses of influence and persuasion were evident in earlier environmental movements of the 1960s and 1970s (McNeill 2000). HIV/AIDS activists in the 1990s drew on their powers of influence and persuasion to mobilize a successful international campaign against the pharmaceutical industry

to create access to low cost antiretroviral drugs in developing countries (Moon 2019). In Latin America, maldistributions of power were reinforced by norms that legitimized inequities. Activists were able to disrupt these norms by mobilizing marginalized groups around new concepts of justice and fairness. Over multiple decades, new norms of fairness contributed to restructuring of institutions that reduced inequality in Latin America in the early years of the 21st century (Evans 2018).

Use of the second dimension of power (rules and norms) to promote the equity dimension of sustainability can be seen in the modern uses of the court system to ensure that the well-being of children and future generations are taken into account in legal and regulatory processes. The lawsuit *Juliana v. United States* is one example of efforts to re-shape institutions to create more equitable outcomes for future generations. The lawsuit, brought by 21 young plaintiffs aged between 11 and 22, alleges that the US government is violating their rights by extracting and burning fossil fuels, emitting CO2, and destabilizing the climate in spite of decades of scientific evidence that these actions significantly harm the well-being of future generations. Other proposed institutional 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 (Boston 2017). Empirical research also supports the importance of using the second dimension of power to promote sustainable development. Wittmayer and colleagues demonstrate that by giving people more active roles in leadership and decision making, community driven social support programs in the Netherlands catalyze "collective processes and alters dominant institutional constellations" leading to more sustainable development pathways (Wittmayer et al., 2017, p. 54). In a very different case, Lubchenco et al. find that efforts to change social norms can influence actors from individuals to firms to countries to fish more sustainably, curb illegal fishing, and create marine reserves (Lubchenco et al. 2016).

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 (Perry, Rothwell, and Harshbarger 2018). 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 power, but these efforts are almost always predicated on strategic use of the second and third dimensions of power (Ganz 2009; Rudel and Hernandez 2017). Current efforts by activists to influence the banking and insurance industries to stop supporting fossil fuel companies are also designed to deprive incumbents of the first dimension of power by limiting their ability to finance extraction of fossil fuels (McKibben 2019).

The capacity to promote equity within and between generations seems necessary for the successful pursuit of sustainable development. Despite the importance of overcoming inequity and maldistributions of power to sustainable development, the literature on empowerment remains relatively limited. Scholars and activists increasingly use John Gaventa's power cube to analyze the three dimensions of power involved in structuring incumbent regimes and their

associated development pathways, the cross-level linkages that often serve to reinforce incumbency, and the spaces and leverage points available to shift development pathways toward more equitable outcomes (Gaventa 2020). But more empirical research on strategies for empowerment as well as legal, regulatory and behavioral approaches to promoting intra and intergenerational equity are needed.

5 CAPACITY TO PROMOTE ADAPTATION

Risk, vulnerability, and resilience

Adaptation[s] has long been an important focus of sustainability science, addressed by a broad range of scholars in different sub-disciplines studying nature-society interactions. Scholars of **risk**[t] highlight the deep and interlinked uncertainties that are a common property of the Anthropocene System and latent in all nature-society interactions (Keys et al. 2019). Scholars of **vulnerability**[u] focus on subpopulations likely to lack or lose access to the resources they need to secure their well-being in the face of threats (Adger 2006). **Resilience**[v] scholars have explored how the characteristics of the Anthropocene as a complex system both support and constrain adaptation (Folke 2016). Research on **innovation systems**[w] (Binz and Truffer 2017) and complexity economics (Elsner 2017) have emphasized how uncertainty and disturbance provide not just threats but also opportunities for novel ways of using resources to advance well-being.

Our own review of these research traditions demonstrated substantial potential for complementarity among the insights of these sub-disciplines. The complementarities are often missed, however, due to siloed scholarship and a related proliferation of similar but slightly and confusingly different terminologies. We do not seek to adjudicate those differences here, but rather to highlight the substantive findings that lie beneath them. Our overall conclusion is that an additional necessary (but, again, not sufficient) condition for sustainable development is the creation and maintenance of a substantial capacity for adaptation, i.e., an ability to confront potentially disruptive change in ways that limit damage, seize opportunities, and secure that capacity for the future. Due to space constraints, we cannot do justice here to the substantial body of primary research behind our argument. Instead, we refer readers interested in the detailed evidence to 4 excellent reviews on which we have drawn extensively in formulating the generalizations that follow: Nelson, Adger, and Brown 2007; Anderies et al. 2013; Eriksen, Nightingale, and Eakin 2015; and Tellman et al. 2018.

5.1 Key Research Findings

5.1.1 Adaptive capacity is necessary for sustainable development

The Anthropocene System is invariably full of **disruptions**[x]: shocks, surprises, innovation and the unfolding unknown (Polasky et al. 2011). Such disruptions are expected from our theoretical understanding of the Anthropocene as a complex adaptive system shaped by multiple feedbacks that shape development pathways but connected across levels of organization to sources or shocks, uncertainty, and novelty (see Section 2). And they are conspicuous in the empirical patterns of nature-society coevolution we discussed in Section 2.

The implications of the inevitable disruptions in the Anthropocene System mean that being on a development pathway that current measurements indicate is "sustainable" (e.g., a pathway on which inclusive wealth, including its equity component, does not decline) is not sufficient to guarantee sustainable development over the long run. Why? Because development pathways that are considered sustainable now will eventually be pushed in unsustainable directions by unexpected disturbances. Moreover, assessments that possible 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. Reciprocally, of course, disturbances can—if they are taken advantage of—push what were believed to be unsustainable development pathways into more sustainable regimes (Farmer et al. 2019).

Whether the Anthropocene System in general, or the subsystems of its component action situations, can successfully pursue sustainability in the face of disturbance depends not only the two capacities already noted (i.e., measuring sustainability and promoting equity) but also on two additional systems properties. First is the system's immediate ability to absorb or otherwise cope with the disturbance in ways that do not irreversibly degrade (and ideally permanently enhance) important dimensions of its functional performance (called by some **robustness**[y]). Second is the system's longer-term ability to reconfigure its use of resources in ways that allow it to effectively function under the new conditions (called by some resilience). These dual capabilities, when effectively harnessed as means to pursue goals of sustainability, constitute the system's **adaptive capacity**[z] for sustainable development. The research challenge is better to understand how such adaptive capacity can be built, maintained, utilized, and evaluated.[19]

5.1.2 Adaptation capacity must be 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 in order 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**[aa] (Leach, Scoones, and Stirling 2010; Wise et al. 2014).

The argument behind this shift is simple, but profound: adaptations, like other attributes of complex adaptive systems, are path dependent. Single adaptations such as behavior change, novel technologies, and new laws and regulations impact the overall dynamics of the system. Those changes (or the anticipation of them) will pose new threats or opportunities both to the original actor and to others that, in response, may undertake their own adaptations. Some of those adaptive (re)actions will further change the system and thus the adaptiveness of actors' strategies. Both theory and empirical evidence suggest that these adaptation cascades can be expected to continue indefinitely and to exhibit substantial path dependence. Moreover, in general the Anthropocene System will be characterized by multiple adaptation pathways driven by multiple strategic actors working at multiple organizational levels (scales) in the context of

[19] The terminological convolutions of this paragraph are a reflection of the multiple and evolving meanings noted earlier for virtually all the concepts discussed in this section. Our intention has been to convey that robustness and resilience in the face of disturbance are system properties that may hinder or facilitate sustainable development. (For the negative case, think "poverty traps.") Adaptive capacity for sustainability, in contrast, is meant to convey the system's ability to redesign or harness its robustness and resilience for the purpose of pursuing sustainability.

multiple action situations. Some of these adaptation pathways will invariably interact with one another, further complicating the picture.

A useful science of sustainability must therefore strive to improve society's capacity to understand the dynamics of these multiple interacting adaptation pathways, and to assess not just immediate local benefits of particular adaptive actions but also foreseeable responses to those actions by other actors elsewhere and later. Since even an improved ability to forecast complex adaptation cascades will remain fallible, research must also seek to understand what might give individual actors and society as a whole the capacity to recalibrate adaptation pathways dynamically in pursuit of sustainability.

5.1.3 Adaptation pathways don't reduce risk so much as redistribute it

The task of assessing and managing adaptation pathways is further complicated by the finding that they often redistribute risk and vulnerability within the Anthropocene System rather than reducing it in any absolute sense. This risk shift phenomenon has been known since Gilbert White's (1945) pioneering work on the management of flood plains. White demonstrated that while levees constructed as an adaptation to reduce the damages from normal floods often were locally and immediately successful, actors then adapted to their reduced vulnerability by building more settlements in the flood plain. This adaptation pathway proved to be maladaptive for society in the long run because when exceptional circumstances eventually led to failure of the levees, damages to the densely settled flood plains were often larger than if the levees had never been built in the first place.

Subsequent studies have explored a wide range of circumstances in which adaptations that mitigate immediate local vulnerability do so by exporting it to other people, places, and times (Adger 2016). These include empirical evidence on dynamic pathways of adaptation and displaced risk that result from (among other things) the suppression of wildfires, the public provision of flood insurance for coastal areas, the adoption of tall smokestacks, and the utilization of pesticides. The theory behind such apparent conservation of fragility is well established for linear control systems, but still lacking is a corresponding general theory for the non-linear systems that characterize most resource management in the Anthropocene (Anderies et al. 2013). Modeling work, however, is beginning to explore tradeoffs between robustness and resilience in such systems (e.g., Homayounfar et al. 2018). And a growing number of case studies convincingly demonstrate how interventions to control short term variability and associated risks in nature-society systems can initiate adaptation pathways that systematically reduce the system's adaptive capacity over longer and larger levels (e.g., Carpenter et al. 2015). A useful science for sustainability must 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 The Determinants of Adaptive Capacity for Sustainable Development

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 researchers have found to be important characteristics of the Anthropocene as a complex adaptive system (see Section 2 and Figure 1). Five, however, stand out: resources, heterogeneity,

connectivity, systems dynamics, and actors. We summarize the most relevant research conclusions immediately below.

The summary account we present here draws heavily on the following reviews, to which we refer the reader interested in the detailed evidence: Brown and Westaway 2011; Biggs et al. 2012; Levin et al. 2013; and de Bruijn et al. 2017. The five 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 most nature-society systems and in the face of most disturbances—even ones with which the system has no prior experience (Carpenter et al. 2012). But, none of these components are without costs, and all must therefore be balanced "Goldilocks-like" to make a useful contribution in any specific action situation. For adaptive capacity, as for other determinants of sustainable development, there are no panaceas. We return to the practical implications of this finding in Section 8 on Governance.

5.2.1 Resources

Adaptation for sustainable development 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 goals. Other things being equal, when resources are more plentiful, the capacity for carrying out such adaptations is greater.

The specific resources that have been shown to matter for adaptive capacity include both the natural and anthropogenic ones we highlighted in Section 3 as the components of inclusive wealth that constitute the determinants of well-being. Indeed, some scholars have argued that the same accounts of capital assets and who has access to them that have been 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?" (Irwin, Gopalakrishnan, and Randall 2016).

The contribution of access to resources in shaping adaptive capacity is consistent with older views from risk assessment that "richer is safer" (Wildavsky 1980) provided that "riches" are denominated as inclusive wealth, i.e., the social value of the resource stock (see Section 3). But it also highlights the potential trade-offs between investments in adaptive capacity such as those listed in the following sections and direct investments in building up the relevant resource stocks and assuring inclusive access to them. The nature and significance of such trade-offs for sustainable development have not yet been adequately illuminated by research.

5.2.2 Heterogeneity

The research summarized in Section 2 has established that a fundamental property of the Anthropocene System is the persistent heterogeneity of its constituent elements. This heterogeneity has been shown to make important contributions to the system's adaptive capacity to support sustainability in at least two ways (Kotschy et al. 2015; Tilman, Isbell, and Cowles 2014). First, it provides the potential for partially compensating losses in well-being resulting from disturbance to particular elements (e.g., a place, a species, an organization, a resource) by offering a source of functionally comparable elements that have avoided or are less sensitive to the disturbance. Second, it provides potential sources of novelty (biological variation,

technological or policy innovation) that the system can draw on for dealing with post-disturbance realities in new ways. The potential contribution of heterogeneity to adaptive capacity can only be realized, however, if it is complemented by appropriate connectivity—a topic we turn to shortly.

Different kinds of heterogeneity have been shown to make different contributions to adaptive capacity. At one extreme is functional *redundancy*: the simple existence of multiple copies of the same elements so that loss of one can made up for by another, e.g., co-pilots or multiple generating stations feeding into an electricity grid. At the other extreme is a *diversity* of fundamentally different options that can be draw on for (partially) meeting the same goals, e.g., different modes for transport or different vegetables for nutrition or different channels through which actors can seek to change unresponsive governance arrangements (e.g., direct appeal to local government vs. appeals through the free press or even twitter).

Evidence is compelling that too little heterogeneity generally detracts from adaptive capacity. And that in particular cases, such as national crop yields, added diversity can have a significant stabilizing effect (Renard and Tilman 2019). Beyond that, however, the picture is less clear. Redundancy and diversity can compete with one another when making more duplicate copies comes at the expense of diversity. And both can come at the cost of efficiency relative to more homogeneous systems well adapted to the circumstances of the moment. Finally, a modest amount of evidence suggests that the contribution of heterogeneity to adaptive capacity is subject to diminishing returns.

5.2.3 Connectivity

Connectivity, as noted in Section 2, is a fundamental attribute of complex adaptive systems in general. In the Anthropocene System it refers to the ways in which the heterogeneous elements discussed in the previous section interact with one another both within and across levels of organization. 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 (Dakos et al. 2015)

High connectivity can allow individual heterogeneous elements to borrow from others, either importing resources from elsewhere to compensate for local damages or providing fertile ground for novelty arising elsewhere. But connectivity can also be maladaptive by propagating disruptions such as disease epidemics or economic panics or by homogenizing system heterogeneities and thereby reducing their potential contributions to the system's adaptive capacity. This has been shown to be the case for situations as different as crop monocultures and the global spread of neo-liberal institutions (Hall and Lamont 2013). Theory and empirical research suggest that a response to these two faces of connectivity has often been 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 support adaptive capacity are poorly understood and almost certainly context dependent.

Progress in resolving how connectivity can be managed to promote adaptive capacity has long been hindered by lack of theory-based empirical language for providing nuanced characterization

of connectivity patterns that include modularity and differential power. That is now beginning to change with the application of network approaches to the assessment of connectivity in Anthropocene Systems (Henry and Vollan 2014). 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 (Bodin et al. 2019).

5.2.4 System dynamics

The dynamical structures of nature-society interactions pose two related challenges for adaptation that must be addressed in building the adaptive capacity necessary to promote sustainable development. The first is associated with the multiple time scales those dynamics entail, the second with their potential for non-reversibility. A sampling of relevant research papers is provided in Biggs et al. (2015).

Multiple time scales

The dynamics of the Anthropocene System involve a variety interactive processes operating at multiple time scales: the slow buildup of infrastructure in a river basin and the flood that suddenly sweeps it all away, the slow decline in crop diversity that leaves a region susceptible to sudden disease pandemics, the slow accumulation of CFCs in the stratosphere that eventually results in a precipitous decline in ozone levels, the slow spread of a norm that eventually supports the viral cascade of changes in behavior. Adaptations can, in principle, address both (relatively) fast and (relatively) slow variables. In practice, however, a variety of factors tend to favor adaptations that mitigate the immediate damages associated with fast variables. These factors range from mechanisms of natural selection, through human cognitive bias, to political short-termism. Too often, this means that the system ends up supporting adaptations to symptoms rather than adaptations that address the underlying causes. Short-term adaptations can certainly benefit immediate well-being. They are insufficient, however, for the effective pursuit of sustainability to the extent that they leave slow dynamics unaddressed.[20] Indeed, they may even erode the capacity to guide adaptation pathways over the long run. The net result is that 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 time scales must include at least two components. The first is 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 Anthropocene System. The enormous body of research on how climate change is driven by the slow accumulation of greenhouse gasses in the atmosphere shows that adequately funded research can obtain such knowledge and use it to evaluate the extent to which alternative adaptation strategies could support sustainable development (e.g., Pershing et al. 2019). The second is governance arrangements that can use such knowledge to support relevant adaptation actions on the ground, a topic we turn to in our larger consideration of governance for sustainability in Section 8.

[20] This shortfall is closely related to the well-known blunder in managing dynamic systems of focusing on flows rather than stocks.

Non-Reversibility

The second systems dynamics challenge that must be addressed in the design of adaptive capacity for sustainable development is the potential for non-reversibility or **hysteresis**[bb] in the Anthropocene System. The normally sensible strategy of adaptation via trial-and-error experimentation ("adaptive management") can fail when thresholds between current development pathways and systems collapse are low, such that thresholds could be easily crossed. For this reason, adaptive capacity must be complemented by the capacity for transition and transformation (see Section 6).

The hysteresis challenge arises because of the non-linear dynamics of nature-society interactions discussed in Section 2 and, in particular, their potential for regime shifts. Research suggests that efforts to build adaptive capacity for sustainable development that can rise to the challenges of hysteresis and regime shifts should be explicitly grounded in a perspective that treats nature-society interactions as complex adaptive systems with the potential to exhibit far-from-equilibrium behavior, multiple attractor domains, and tipping points (Bohensky et al. 2015).

The challenges of hysteresis requires that efforts to build adaptive capacity pay specific attention to 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. As discussed at greater length in the publications cited at the beginning of this section, research 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., Steffen et al. 2018; Schlüter et al. 2019). 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 (Downing et al. 2019). Promising theoretical work on the prospects 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 systems (Scheffer et al. 2018; Scheffer et al. 2015).

5.2.5 Actors

Who benefits and who loses from the redistribution of risks that occurs along adaptation pathways is not random. Rather, it is determined as an outcome of the continuing coevolution of nature and society within which some people have more power than others over how risks are experienced and articulated, causation is attributed, adaptations are formulated, decisions are made, and outcomes are evaluated (Eriksen, Nightingale, and Eakin 2015; Wise et al. 2014). The result has been a highly uneven distribution of risk and vulnerability at all levels of organization: household, community, regional, and national (Brown and Westaway 2011). Human agency matters in shaping this distribution (e.g., Tellman et al. 2018). But (as discussed in Section 4) it is usually the actors with power who have greater capacity to shape adaptation pathways. And they generally do so in ways that that protect or promote their immediate interests, shifting risks through adaptation pathways toward those actors who are relatively powerless. The mechanisms of a relative lack of power by some can stem from lack of access to resources, exclusion from

decision making processes, and the influence of powerful actors on collective understandings of risks and opportunities for adaptation (see Box 1). 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 than in previous eras of nature-society interactions, rendering even actors with substantial local adaptive capacity increasingly vulnerable to disruptions beyond their immediate control. We conclude that a central, though 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. Looking ahead, we argue in Section 6 that power is even more central where adaptations aim to bring about large-scale transformation of major components of the Anthropocene System.

6 CAPACITY TO PROMOTE TRANSFORMATION

Innovation, assessment, imagination and incumbency

"Transformations" are shifts from one regime and its associated development pathways to another. **Sustainability transformations**[cc] are shifts from regimes associated with unsustainable pathways of development to alternative regimes in which development pathways are (provisionally thought to be) sustainable. One example of a change in development pathways that has been presented as a potential sustainability transition is the shift from energy regimes dominated by fossil fuels to energy regimes dominated by renewables (Geels et al. 2017). Another is the shift from fishery regimes locked in downward spirals of overexploitation resulting in degradation to both fish and fishers to regimes characterized by sustainable fishing practices and sufficient marine protected areas to sustain the population (Lubchenco et al. 2016).

The sustainability science community has long been interested in the concepts of system transformation or transition. (We treat the two terms as referring to similar phenomena.[21]) The 1999 United States National Research Council Report on sustainable development emphasized the transitions perspective in its full title "Our Common Journey: A Transition to Sustainability." The following year, the world's scientific communities gathered for a conference titled "Transition to Sustainability in the 21st Century." A generation later these scientific perspectives had been adopted by the UN as it articulated its 2030 agenda for sustainable development in a document entitled "Transforming our world." More broadly, transformations for sustainability have increasingly become a focus of social and political discourse around the world as concern over the intertwined crises of current development paths become clear (Wibeck et al. 2019).

[21] The literature addresses sustainability transformations and transitions without consistent distinctions between them (Hölscher, Wittmayer, and Loorbach 2018). Both terms are usually used to refer to non-linear and structural change in a development pathway. The term 'transitions' is used more frequently by the socio-technical transitions research community and transformations is used more frequently by scholars of resilience and adaptation in social-ecological systems, but even this sub-disciplinary distinction is often blurred. Some scholars have defined 'transformations' as more radical or large-scale 'transitions' connecting multiple sectors or action situations. But the distinction between transformations and transitions is sufficiently ambiguous that a new term "deep transitions" is increasingly being used to describe the cumulative impacts on macro-level elements and relationships of large-scale and interconnected structural change across multiple action situations and development pathways (Kanger and Schot 2019). We use the term "transformation" because of its close association with current high-level sustainability debates, e.g., the UN's "Transforming our world: The 2030 agenda for sustainable development."

Research communities across sub-disciplines in sustainability science are concerned with the dynamics of transformations, but their focus is often siloed to one or two resources of interest. Ecologists for example focus on transformations in ecological resources such as transformations from net deforestation to net reforestation in a specific action situation (Meyfroidt and Lambin 2011; Rudel et al. 2020). Likewise, scholars of demography and environmental change focus on the multiple drivers of demographic transformations and their varied impacts on natural resources (J. Barnett and Adger 2018), while scholars of social metabolism look at transformations in the extraction, trade, and use of materials often across multiple action situations or regions and their associated impact on the possibilities of larger transformations toward sustainability (Schaffartzik et al. 2014; Haberl et al. 2019). The socio-technical research community focuses on the dynamics of transformations in technology and institutions (Köhler et al. 2019).

6.1 Key Research Findings

A community of research has grown over the past decade with the goal of understanding how to support or manage transformations to more sustainable regimes and their associated development pathways. We cannot do justice here to the substantial body of literature that this community is producing. Instead we refer readers interested in a deeper dive into sustainability transformations (or transitions) to four papers that review the growth of this field and synthesize results (Loorbach, Frantzeskaki, and Avelino 2017; Scoones 2016; Markard, Raven, and Truffer 2012; Geels 2019). We draw heavily on these reviews for the summary of results provided here. That said, we endeavor to embed their findings, based largely in the study of technological systems, into the broader framework of the Anthropocene System we have employed in this review. In sections 6.1 and 6.2, we describe the key research findings of this field and point to knowledge still needed to strengthen society's capacity to promote transformations toward sustainability.

6.1.1 **Transformative capacity**[dd] is necessary for sustainable development

Transformations are related to but significantly different from the adaptations we discussed in Section 5. Adaptations generally seek to keep systems within current regimes and their associated development pathways. Transformations, in contrast, involve shifts across regime thresholds resulting in future development pathways that are qualitatively different than they would have been if the regime shift had not occurred. When current regimes are unsustainable, tendencies towards path-dependence and lock-in can make incremental adaptation an insufficient and even counter-productive strategy for the successful pursuit of sustainability over the long run (Díaz et al. 2019). An emphasis on capacity for transformation goes beyond capacity for adaptation to change the focus from avoiding bad regimes, to actively supporting transformations toward more sustainable regimes (O'Brien 2012). Research, in short, has made a compelling case that a capacity for promoting qualitative transformations of regimes and their associated development pathways is necessary (but not sufficient) for sustainable development.

6.1.2 Transformative capacity must be dynamic

Each of the research communities working on transformation addresses regime shifts. But each initially tended to focus on particular action situations and distinct subsets of full array of elements and relationships that research has shown to be important in shaping pathways of development in the Anthropocene System (see Section 2 and Figure 1). For example, early work by scholars in ecology and climate science generally focused on transformations defined by

regime shifts in the development pathways of natural resources under external forcing by selected social dynamics. In contrast, the community of scholars working on socio-technical transitions initially focused on transformations in the dynamics of anthropogenic resources—particularly technology and institutions—while largely ignoring the role of change in the system's natural resources. More recent research on transformations, however, is increasingly embracing the core sustainability science finding that nature and society are intertwined in deeply co-evolutionary relationships that shape dynamical pathways of development (Ahlborg et al. 2019). Transformation research is coming to acknowledge that due to the deep complexity of the Anthropocene System interventions intended to impact natural resources will almost always impact social resources in the same regime. At the same time, changes in society (including its technologies) will impact nature (Loorbach, Frantzeskaki, and Avelino 2017). Transformations, like adaptations, are coming to be seen not as discrete events confined to specific resources of interest (e.g., fuel sources for energy systems) but rather as dynamical cascades entailing multi-dimensional regime shifts and associated qualitative changes in development pathways (Rocha et al. 2018). The implications of this dynamic character of transformation pathways for efforts to build capacity for guiding, much less managing, them has not yet been adequately explored.

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 in order to create inclusive well-being. 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, but also in institutions, politics, and social goals for sustainability. 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. Long missing from sustainability science, however, was much in the way of 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 (Anadon et al. 2016; Binz and Truffer 2017; Kattel and Mazzucato 2018).

This unsatisfactory state of affairs has itself been transformed through the gradual adoption into the mainstream of sustainability science of an initially independent but rapidly maturing program on the history and theory of large scale socio-technical transitions (Loorbach, Frantzeskaki, and Avelino 2017) This 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 is the **multi-level perspective (MLP)**[ee] from which the Sustainability Science Framework we presented in Figure 1 draws a great deal of inspiration (Geels 2019). The MLP takes as its point of departure the observation that in any given action situation, dominant development pathways are structured by incumbent regimes (see Section 4). The positive feedbacks of the regime create path dependencies that make transformations to new development pathways difficult. Exogenous variables at higher levels of organization such as global economic systems, wars, and climate change put pressure on incumbent regimes which can sometimes create openings for changes in incumbent regimes. However, changes in the incumbent regime are unlikely without sources of novelty that usually

originate at micro-levels of organization. Novelty can take many forms including new or re-combined traits of technologies and practices as originally highlighted in the MLP approach, but more broadly also encompassing organisms; institutional structures; actors' goals, values or behaviors; and knowledge about the Anthropocene System.

The MLP and the literature on strategic niche management (SNM) 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 co-evolution of technology, user practices, and regulatory structures shielded from the forces of dominant regime structures (Sengers, Wieczorek, and Raven 2019). Managing connectivity between the micro- and meso-level is important for transforming development pathways, just as it is for adaptation. Too much connectivity from meso-level to micro-level and the protective niche can be swamped, prematurely subjecting immature innovations to the rigors of a wider world. But too little connectivity from the micro- to the meso-level can inhibit the spread of novelty as it matures. Studies focused on connectivity between the micro- and meso-level demonstrate that it is not the quantity of connections but rather the type of connections that determine whether novelty that supports transformations for sustainability will be able to break out of the micro-level into the meso-level regime. The flows of novelty from the micro-level to the meso-level are influenced not only by the appropriateness of an innovation itself, but also by selection rules of the relevant regime (Hausknost and Haas 2019). The meso-level configurations of actors, institutions, and available resources of the regime create a selection environment that determines which kinds of novelties are repressed or ignored, and which have the chance of emerging from protected niches into widespread use. Actors seeking to transform development pathways must therefore attempt to change the selection environment created by the relevant regime. For example, with a goal of reducing greenhouse gas emissions through adoption of low-carbon technologies, policy interventions that focus on institutional variables related to technology selection are at least as important as policies that support research and development for the design of technology itself (Schot and Steinmueller 2018; Fagerberg 2018).

6.2 Challenges for Building Transformative Capacity

The capacities for adaptation and transformation are not unrelated. Both take as their starting point the complex adaptive nature of the Anthropocene System and therefore must contend with issues of path-dependence, connectivity, and heterogeneity. But three challenges for building transformation capacity merit special attention: promoting collective visions of what sustainability transformations of the Anthropocene System might look like; integrating sectoral transitions into a system level transformation for sustainability; tackling the resistance of powerful incumbents to meaningful transformations.

6.2.1 Transformations to what? Integrating anticipation and imagination

Transformations to what? The question needs answering, since 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" (Burch et al. 2019, 11), 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 alternatives interventions designed to avoid or mitigate the dangers. Common methods employed in anticipatory research include modeling, assessments, foresight exercises, and some forms of scenario building (Cashore et al. 2019; Spangenberg 2019; Venkataraman 2019).[22] Examples run from the early *Limits to Growth* studies that helped to usher in modern concern for sustainability through the recent work of the Intergovernmental Panel on Climate Change on the dangers of, and prospects for avoiding, a global temperature rise of 1.5 degrees C. The strength of such approaches is that—at their best—they can make systematic use of scientific data, facts, and causal relationships; can be transparent enough to be subject to critical review; and can involve both multiple forms of expertise and multiple potential users in their execution. (We further explore these latter issues of linking knowledge with action in Section 7). Transformation research guided by such anticipatory studies is largely about shifting away from development pathways that risk being unsustainable.

Imagination-driven approaches 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. Examples include the Brundtland Commission's seminal vision of development pathways that meets the needs of the present without compromising the ability of future generations to meet their own needs—a vision that certainly made use of science but one that was ultimately based on a radical (for its day) act of imagination. Later relevant imagination-driven efforts in the public sphere include the vision of *The Future We Want* produced as the outcome document for the 2012 UN Conference on Sustainable Development and the Sustainable Development Goals (SDGs) approved by the UN three years later. The strength of such approaches is that they invite normative grounding and aspirational thinking and, even more than anticipatory approaches, have proven themselves open to deliberative construction involving a wide range of stakeholders. Scholarly work has provided valuable foundations for this work. An early example is the work of the *Global Scenarios Group* and its successor *The Great Transition Initiative* (Raskin 2016). Subsequent efforts in this area are evident in the creative use of imagination-driven scenarios in the Millennium Ecosystem Assessment and its successor the IPBES (Sitas et al. 2019).

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 (e.g., Pereira et al. 2019; Narayan and Tidström 2019; Hajer and Versteeg 2019) and plans for achieving them. What is becoming clear in all of these approaches, however, is the implicit conservatism of most efforts to address the "Transformation for what?" question. In particular, most efforts leave unchanged existing assumptions about relevant actors, institutions, and power structures much as Jules Verne's novels combined inspired imagination about novel technologies with uncritical acceptance of the durability of Victorian social arrangements. This is especially serious given the growing recognition that the unsustainability of many contemporary

[22] A critical review of these and related methods in the context of sustainable development would be most useful. We regret that there was simply no space to offer such a review here.

development regimes is due in large part to current configurations of actors, power, and institutions (see Stirling 2019 and Section 6.3).

The narrow framing of most efforts to envision sustainability transformations is now being questioned by scholarship on the importance for social change of shared **imaginaries**[ff] (Schot and Steinmueller 2018). Imaginaries are collectively held visions of good or attainable futures that serve to envision the possible and motivate action towards new development pathways (Jasanoff and Kim 2015). 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 (Schot and Kanger 2018; J. Beckert and Bronk 2018). Empirical work on shared imaginaries and social change demonstrates that they can originate from the visions of single individuals and small groups through a process of envisioning, embedding, resistance, and extension (Jasanoff and Kim 2015). The fact that collectively held imaginaries can originate from the efforts of a small number of powerful actors raises important questions about where imaginaries come from and whose interests are furthered by dominant imaginaries. Schot and Kanger (2018) argue that industrial modernity constitutes our most widely held and pervasive imaginary, which over the past 250 years led to both increasing wealth and welfare in the western world, but also to increasing inequality and ecological degradation. At the same time, scholars of social movements argue that the success of the various rights movements in the United States in the 20th century were predicated on the ability of the movements to build clear and specific imagined futures that were strong enough to motivate collective agitation in the face of deep uncertainty and risk (Venkataraman 2019; Ganz 2009).

But if the industrial modernity imaginary led to current crises of unsustainability, what are the prospects for creating collectively held sustainability imaginaries that create visions of good and attainable futures and justify investments in research and development and scale-up of more sustainable technologies and socio-technical 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 (D. White 2019; Ocasio-Cortez 2019). The challenge for sustainability science is, once again, to catch up with practice in their explorations of the question "Transformations for what?" The essence of this challenge is to build a capacity for generating answers that simultaneously encourage pluralistic, context-specific answers to the question but also create shared visions that can help to guide collective action to achieve results (see also Section 8).

6.2.2 Integrating sectoral transitions into system-level sustainability transformation

A second challenge in building a capacity for sustainability transformations is to better understand the extent to which it would be useful explicitly to combine work on transitions in particular sectors into a vision of sustainability transformation per se. Several recent efforts have attempted to categorize the 17 SDGs into smaller groups of coherent transformation goals (Sachs et al. 2019; Schot et al. 2018). This approach is in line with the majority of research on transformations, which as we noted earlier is focused on particular action situations, usually sectors in particular places. But we also noted in Section 2.2 that multiple action situations are always in play in the world and that developments in one frequently affect the others. The classic case we cited there is the nexus of interactions among the energy, water, and agriculture sectors

(Nepal et al. 2019). Despite the general recognition of the nexus problem, however, very little research on transformations has yet addressed the possibility that the benefits of a sustainability transformation in the development pathways for one sector or other action situation could undermine or offset transformation efforts in another.

There are clearly advantages to this partitioning of transformation research. For example, Geels et al. make a compelling case that focusing transition work on particular production-consumption systems would make feasible the construction and testing of mid-range theories that could usefully inform and hold accountable action in particular ministries and firms (Geels et al. 2015). It is not clear that our understanding of nexus interactions is yet sufficiently advanced to justify pushing transformation research to integrate across them. On the other hand, as we pointed out in Section 3, one of the most significant advances in sustainability science over the last decades has been the development of a theory-grounded, operational, and useful set of measures to assess the state of sustainable development per se, i.e., measures of inclusive wealth. The sustainability science community should almost certainly seek to combine its advances in measuring sustainability and in understanding sustainability transformation. 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 proposed. In particular, we are unaware of work that seeks to evaluate whether a specific transformation is likely to shift development pathways in ways that would be assessed to be sustainable in terms of the full suite of natural and anthropogenic resources discussed in Section 3. In efforts to determine what would constitute a capacity for advancing sustainability transformations, such research is certainly worth exploring.

6.2.3 Confronting incumbency

The ability to foster novelty, as noted above, is important and probably essential for regime transformation. But regimes are often resistant to novelty, whether it comes as new organisms, technologies, practices, institutions, or knowledge (Loorbach, Frantzeskaki, and Avelino 2017; Kuchler and Bridge 2018). The path dependency of regimes has two causes, one passive and one active. The passive cause of path dependency, 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 (Foxon 2011). An example of this type of passive path dependency is the continued preference for gas-powered over electric powered vehicles due to the relative abundance of gas stations relative to electric recharging stations on US roadways. The supply of gas stations compared electric recharging stations creates selection pressures that favor gas driven vehicles and disadvantage electric vehicles.

The active cause of path dependency in regimes are actions by powerful actors to block novelty that threatens the established position of winners in incumbent regimes. Powerful actors who benefit from the distribution of resource flows created by incumbent regimes can mobilize multiple dimensions of power (see Section 4) to reinforce incumbent regimes and protect their continued advantage. For example, barriers to transformation in the auto industry are not only the result of increasing returns to scale, but due to active efforts by incumbents to maintain regime

stability and undermine "greener" socio-technical regimes (Wells and Nieuwenhuis 2012). Indeed powerful incumbents demonstrate a nuanced ability to not only 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 incumbent regimes (Bakker 2014; Apajalahti, Temmes, and Lempiälä 2018). An ability to generate novelty is almost always a prerequisite for regime transformation. But an ability to destabilize existing regimes is at least as important but perhaps more challenging. It should thus be at the cutting edge of transformation research for sustainability.

Research to date strongly suggests that multiple actors must be involved in overcoming existing regime structures and supporting transformation to new regimes (Wittmayer et al. 2017). Actors play roles at different levels or organization from creating innovations and supporting strategic niche management at the micro-level, to meso-level changes in laws and regulations that select for novelty more likely to support sustainable development, to widespread social movements aimed at shifting macro-level pressures such as the forces of globalization (Fischer and Newig 2016). Actors also play important roles in driving social movements and other creative forms of collective action (McGee and Pettit 2019) and in creating collective imaginaries to drive transformations toward sustainable development (Longhurst and Chilvers 2019; Pereira et al. 2018).

Researchers are actors too, and sustainability scholars also must be actively engaged in confronting incumbency (see Section 7). Yet despite increasing awareness of the importance of actors in overcoming incumbent regimes, the literature on sustainability transformations still lacks strong theoretical or empirical guidance on the diversity of actor roles in transformation or guidance matching actors, the types of power and authority they command to efforts to support transformations across different levels of organization or different stages in the transformation process. Such research—and the active engagement in confronting incumbency that goes with it—is needed to inform the creation of a capacity to systematically and effectively advance sustainability transformations.

7 CAPACITY TO LINK KNOWLEDGE WITH ACTION

Co-production, boundary work, decision support

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. But it must also be used in order to generate social value. The sustainability science research we have reviewed in previous sections of this paper has largely dealt with the production of knowledge that has the potential to support sustainable development. But though the production of the research may have been use inspired, much of it remains unused in practice. And many potential consumers of research working on the front lines of action for sustainable development continue to lament the lack of knowledge they most need. These gaps between what is known or knowable about sustainable development and what is applied on the ground have long been recognized but are receiving renewed attention in the scholarly community (ICSU and ISSC 2015; J. Liu et al. 2019; Turnhout, Tuinstra, and Halffman 2019). 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.

7.1 The Co-Production of Knowledge and Society

The most fundamental finding that research has brought to the challenge of linking knowledge with action is the idea of **co-production**[gg]. The essence of the idea is that knowledge and society continually reshape one another (Forsyth 2003, 104). What questions are (not) asked, whose evidence is (not) considered, and which sorts of explanations (don't) 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 (Wyborn et al. 2019). 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 some highlights that help to set the stage for the capacity arguments that follow.

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 at its core is 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.

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 natural scientists, social scientists, and scholars trained in the humanities 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 scientists to include actors with relevant indigenous and local knowledge (ILK) or knowledge gained from practice. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has been a leader in recent efforts to improve the diversity of expertise participating in assessments of nature-society interactions (Pascual et al. 2017). A recent review of its efforts, accomplishments, and remaining challenges provides an excellent perspective of contemporary thinking about participation and inclusiveness in sustainability efforts more generally (Díaz-Reviriego, Turnhout, and Beck 2019). 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.

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 (Fischhoff 2019). 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 coproduction in which potential users come to see knowledge products as meeting the criteria of saliency, credibility, and legitimacy (Daly and Dilling 2019). Available evidence suggests that at least minimum levels of performance on each criterion are necessary to achieve influence (Clark, Tomich, et al. 2016). A balanced approach is needed. Going to extreme lengths to assure scientific credibility through peer review may be 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 (Turnhout, Tuinstra, and Halffman 2019).

Relevant to both objectives noted above is the fact that participation is almost always expensive for participants. Obvious costs are time or other scarce resources. But reputational risks (for experts) and political risks (for stakeholders) can also be important (Oliver, Kothari, and Mays 2019). The pursuit of sustainability, as we have emphasized throughout this review, is an inherently political activity conducted in presence of strong incumbent interests and substantial power differentials among actors. Because knowledge is 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 less mainstream knowledge and interests—has the potential to either undermine or strengthen those participants' own positions (Clark, van Kerkhoff, et al. 2016). The focus of recent co-production scholarship on participation and inclusiveness is certainly 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 to secure at what stages of dynamic efforts to link knowledge with action (Wyborn et al. 2019; Grillos 2019).

7.2 Capacity Building to Link Knowledge with Action

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 (van Kerkhoff and Lebel 2015; Clark, van Kerkhoff, et al. 2016).

Suitably trained researchers can significantly enhance their capacity to better 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 the importance 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 front line action. And a growing number of courses and training programs are available (Evans 2019). 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 more better and more accessible training programs are needed (West, van Kerkhoff, and Wagenaar 2019). Many approaches are being tried around the world (Giangrande et al. 2019). An effort to pool lessons from these ongoing experiments would almost certainly be useful, though 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. That said, one general need that has become evident in our research for this review is a small shared set of empirically rich, long duration histories of efforts to link knowledge with action for sustainability. Almost every successful field we know has some such set of shared puzzles that serve as common reference points for comparison of perspectives and methods. Sustainability science could do with some too.

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 (Social Learning Group et al. 2001). 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 (de Kraker 2017). Because the system is complex, it will surprise us. Because it is adaptive, novelty will drive it, making how it works tomorrow different from how it worked yesterday. Because it is heterogeneous, experience in one location is an important but perilous guide to action in another. Societies therefore have limited ability to predict how development pathways will unfold or how particular interventions meant to guide those pathways toward sustainability will in fact work out. Rather, they must treat interventions experimentally, work to anticipate difficulties, but ultimately learn by doing. The ability to do this effectively, rather than becoming stuck in ruts of old but no longer valid knowledge, has been shown to benefit from mindsets that recognize the complex adaptive character of the Anthropocene, from the creation of organizational **safe spaces**[hh] that encourage experimentation and the timely acknowledgment of error, from an appreciation of the co-produced character of useable knowledge, and from an abiding humility of researches as we confront the tasks before us (Siebenhüner, Rodela, and Ecker 2016; Suškevičs et al. 2018; Gerlak et al. 2018).

Building capacity to link knowledge with action for sustainability also requires investing in organizations to carry out the **boundary work**[ii] of connecting experts and decision makers (Clark, Tomich, et al. 2016). 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 advisory system most likely to mobilize knowledge effectively. One of the most demanding situations is when 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 (Mitchell et al. 2006; Kohler 2020). 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 (Clark, Dickson, and Matson 2016), but with special emphasis in the context of advice for dealing with climate change (Palutikof, Street, and Gardiner 2019). 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 (Webber 2019; Cashore et al. 2019). Like all organizations, decision support efforts are prone to getting caught in ruts, captured by particular interests (be they academic disciplines or particular users), and simple exhaustion. If they are to guide development pathways toward sustainability over the long run, boundary organizations need themselves to be learning organizations assisted in their efforts by periodic external reviews (Weichselgartner and Arheimer 2019).

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 since knowledge creation is so intertwined with society and its power structures, the research that is likely to be most readily funded and is likely to be most readily adopted by decision makers is research that supports (or at least does not threaten) the status quo, meaning the development paths we are on. For a lot of sustainability issues, these potential entanglements may be relatively unproblematic. But the risk is real that knowledge most needed by marginalized groups or interests won't get produced, as exemplified by the continuing struggle for drugs to treat neglected diseases (Ferreira and Andricopulo 2019). 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 push back, 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 (Farrell 2019; Nestle 2016). 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 (Middeldorp and Billon 2019). 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 turn to what is known about the character and performance of such arrangements in the next and final section of our review.

8 CAPACITY TO GOVERN FOR SUSTAINABILITY

The commons, collective behavior, panaceas, norms

Governance, as we noted in Section 2.2, is 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's desirable and in doing the steering) and about results (does the steering get 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. Indeed, at the global level there is no government. But there is governance (Ruggie 2014).

Governance for sustainable development pays specific attention to the resources (both natural and anthropogenic) that society draws on to meet its goals. It thus involves all the key elements of the Anthropocene System summarized in the Sustainability Science Framework 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.

Some treatments of sustainable development view the work 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 sustainability, value denominated as inclusive well-being (Mazzucato 2018). There will certainly be cases in which, as an empirical matter, markets will be the best available means for guiding collective action toward such valued outcomes. But given the ubiquity of market failures in matters central to sustainability—responsible use of the environment, promoting intergenerational equity, serving marginalized populations, etc.—such cases will be rare unless firms reimagine their roles, and the roles of capitalism more generally, in the Anthropocene (Henderson 2020). The governance arrangements most likely to promote sustainability seem likely to involve a mix of public and private actors, market and regulatory incentives, and adoptions of norms that strengthen responsibility for promoting the public good. Those are not the arrangements that characterize the world today, which are held firmly in place by a combination of path dependency and incumbency (Stirling 2019). Building governance arrangements that have any realistic hope of advancing sustainable development is therefore an inherently radical enterprise committed to disrupting the status quo. Politically engaged agitators are necessarily the frontline change agents of such a movement. But research can seek to inform agitation, providing diagnoses of the obstacles today plus recommendations for fostering the capacity to govern for sustainability (Adger and Jordan 2009).

A growing number of scholars have pursued research to inform governance for sustainability over the past several decades. That work continues and is now being systematically advanced through a vigorous international program on Earth System Governance (Burch et al. 2019).[23] We summarize here some of the most important findings of that research. We refer the reader interested in more extended coverage of the field to books by Adger and Jordan (2009), Young (2017) and Dryzak and Pickering (2018).

8.1 General Trends in Governance Relevant to Sustainable Development

Today's governance arrangements are the path dependent product of efforts to solve the problems and seize the opportunities of previous centuries. Those historically shaped arrangements provide the foundation for governance that the world now has available for its pursuit of sustainability. That said, several general trends in governance have emerged over the last several decades that are shifting its foundations in ways that are particularly relevant for the pursuit of sustainability.

[23] The formal title of the program can be misleading as it reflects its origins in studies of global environmental governance. Its current content, however, is entirely consistent with what would, in the terminology of this review, be called something like "governance of the Anthropocene System." Its research reflects multiple levels of organization, multiple actors, and a diverse array of governance arrangements.

8.1.1 Rescaling of governance

The most general of these governance trends is the rescaling of governance arrangements (Andonova and Mitchell 2010; Hale 2020). Three dimensions of this rescaling have received the greatest attention. The first involves spatial scale. Efforts to craft governance arrangements once focused largely on the local or national level. But the general trend toward globalization has brought forth an increasing number of governance efforts that transcend national borders. Governance today operates not just at single levels of organization but at multiple, interacting levels spanning the local through the national to the global (Brondizio, Ostrom, and Young 2009). A second dimension of rescaling involves actors. Governance increasingly involves not just governments but also firms and other private sector organizations, a blossoming array of non-governmental organizations and active participation by civil society. Reimagined private firms (Henderson 2020) and novel public-private partnerships of governance entrepreneurs (Pattberg and Widerberg 2016; Andonova 2017) are increasingly active in seeking to guide behaviors relevant to sustainability. A third trend has been toward linkage among issues or, in the terminology introduced in Section 2, linkage among action situations. Governance initiatives in particular sectors—economic, environmental, or social—increasingly find themselves intertwined with one another, as do efforts to govern particular places (Bleischwitz et al. 2018).

The three dimensions of rescaling noted here frequently interact with one another. The result has been new varieties of **polycentric**[jj] 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 (Ostrom 2010). Polycentric governance has been argued to hold potential advantages over more traditional monocentric arrangements to the extent that it can involve more inclusive representation and consequently more legitimacy, can encourage innovative experimentation, and can have greater flexibility in responding to changing circumstances (Jordan et al. 2018). But empirical research shows that it can also confront actors with excessive transaction costs, contradictory signals, the hazards of free-riding, hidden power dynamics, and overall failure to guide collective behavior toward desirable outcomes (Morrison et al. 2019).

8.1.2 Expanding the toolkit

An additional broad trend in governance has been the expansion of the toolkit of interventions it employs. Formal rules and regulations, together with mechanisms for encouraging compliance, have long been the focus of governance scholars and practitioners. Market mechanisms have been increasingly in vogue. Creative applications of these will almost certainly remain important components of efforts to guide collective behavior toward more sustainable outcomes (e.g., Heilmayr and Lambin 2016). But efforts to shape governance arrangements for sustainability are increasingly exploring complementary tools. Generative tasks such as identifying emergent issues and pushing them on public agendas are coming to be seen as core components of governance, not something to be left only to experts (Romsdahl, Blue, and Kirilenko 2018). The potential role of behavioral nudges rather than rigid commands is receiving increasing attention (Bornemann 2019; Kuehnhanss 2019; Sunstein and Reisch 2014). Principled governance through the promotion of norms at all levels has also seen significant growth (Mitchell and Carpenter 2019), most recently including a focus on responsibilities as well as rights of various actors (Henderson 2020; Sikkink 2020). Finally, a movement toward governing through goals has gained strength, with perhaps its most ambitious incarnation in the UN's system of Sustainable

Development Goals (Kanie and Biermann 2017). This expanded array of governance tools is increasingly being deployed in novel combinations to address the challenges of sustainable development (Ruggie 2014; Young 2017). Still lacking, however, is a "user guide" to aid governance entrepreneurs in matching specific tools to specific tasks under specific political circumstances.

8.1.3 Rejecting panaceas, striving for fit

A third relevant trend in governance starts with a negative: the growing (if still incomplete) rejection of panaceas claiming to be the one right way to guide collective behavior independent of particular resources, actors, power distributions, or action situations at hand (Ostrom, Janssen, and Anderies 2007). The most popular panacea advocated for governing nature-society interactions is perhaps that of the philosopher king. But private ownership, market solutions, participatory management, the polycentric governance noted above, and a variety of other enthusiasms have also had their days. Each of these governance arrangements has value in particular situations and contexts. Each has also failed dramatically when applied to action situations where it does not fit. Indeed, the "problem of fit" has emerged as a central preoccupation of contemporary governance scholarship (Epstein et al. 2015). In essence, research has found that a necessary condition for effective governance arrangements is that they be well-matched to the particular action situation they are intended to steer. This general finding of the importance of **fit**[kk] is consistent with what we know about the central role of persistent heterogeneity in the complex adaptive system that is 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. And to figure out how the resulting mix can be sufficiently integrated to be mutually supportive in guiding collective action (Brown 2009)—a challenge given added urgency by the diversity of the UN Sustainable Development Goals (LeBlanc 2015).

8.1.4 Mismatch between growing demands on governance and its ability to deliver

The last trend we cover here is perhaps less well developed than the others but no less important: the growing mismatch between the expectations placed on governance arrangements and the actual ability to fulfill them (Andrews, Pritchett, and Woolcock 2017; Berwick and Christia 2018). The difficulty is not new: unfunded mandates have always plagued governance. But the proliferating problems of the Anthropocene are eliciting increasing calls for governance to guide collective behavior. And an increasing number and variety of actors have responded to the demand by entering the governance arena. There they have often ended up competing for mandates, people and money needed to make meaningful contributions. The result has often been disappointing, leaving society facing too many acronymed actors with no clear role to play, too little concentration of scarce resources to make a real difference, too many annoying but toothless regulations, too little accountability for results, and too often a resulting decline in the trust and social capital that governance is meant to build (Young 2017). The UN's SDG 17 acknowledges the importance of increasing the overall ability of governance to support sustainable development, as did the original report of the Brundtland Commission. But neither has much specific to say about how this essential job is to be done. We focus in what follows on what research has discovered about how governance arrangements can contribute to the specific capacities that we have argued in previous sections are necessary for sustainable development.

8.2 Building Effective Governance Capacity

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 (Dryzek and Pickering 2018). Improvements in governance are needed in general, but particularly to support the capacities for sustainable development we discussed in earlier sections of this review. That said, our reading of the evidence suggests that many of the same governance reforms could help strengthen multiple capacities. We therefore focus here on three big areas of governance reform that scholars have argued have the potential to provide such cross-cutting benefits for sustainable development: nurturing resources, enhancing equity and embracing uncertainty (Anderies 2015).

8.2.1 Nurturing shared resources

A central challenge of governance for sustainable development is to guide the use of shared resources today down pathways that do not degrade the ability of those resources to nurture well-being elsewhere or tomorrow.[24] 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 governance for sustainability has focused on two dimensions of this challenge: preventing overconsumption of shared natural resources and preventing underproduction of shared anthropogenic resources.

8.2.1.1 Overconsumption of natural resources

The concern that individual actors will overconsume natural resources to the detriment of social well-being has been central to sustainability research since the earliest work on how to avoid overharvesting fisheries and forests. But pollution issues can usefully be viewed from the same perspective as overconsumption of the environment's limited ability to disperse or detoxify what we throw into it. These concerns were given a boost by Garrett Hardin's brilliantly titled, conceptually flawed, but highly provocative essay on the "tragedy of the commons" (Hardin 1968). Hardin postulated that the only way to prevent overexploitation of open access natural resource commons was through external imposition of an all-powerful regulator (often the state) or of private ownership. This view is consistent with popular governance arrangements involving state protected areas, resource privatization, pollution regulation, the use of marketable permits, and the like. Other scholars, however, pointed out that Hardin's prescriptions often failed, that there existed many instances in which actors had self-organized successful collective action arrangements to share the use of common resources, and that the quest for single "panaceas" for

[24] The challenge has been theorized in terms of distinction among resources that are "private," "common pool," or "public," with definitions based on whether consumption of the goods or services flowing from the resource is excludable or rivalrous, and whether effective governance requires cooperation of a few actors or many (Sandler 2004; S. Barrett 2007). The theory has been helpful in clarifying issues. But empirical work has revealed that particular resources used in particular action situations often fail to conform to the theoretical architypes. Rather, they exhibit, or have the potential to exhibit, a mix of characteristics determined not solely by characteristics of the resource but also by its history of use, by the actors involved in decision making about it, and the institutions that govern it (Kaul 2012a; Barkin and Rashchupkina 2017; Frischmann, Marciano, and Ramello 2019). In this review we build on the well-established and elegant public goods theory cited above but take what others have called a "relaxed" or inclusive view of public goods, focused on anthropogenic resources that are potentially public in consumption. Our concern is simply how to enhance those resources' net value to society over the long run (Estevadeordal and Goodman 2017a).

governing resource use was singularly misguided for dealing with the complex and adaptive systems of the Anthropocene (Ostrom, Janssen, and Anderies 2007).

Elinor Ostrom led a vigorous, diverse, multidisciplinary research program seeking to identify the conditions under which and ways in which self-interested actors have worked together to achieve common goals (McGinnis and Ostrom 2014). That program has produced, tested, and continues to elaborate a set of guidelines for identifying governance arrangements likely to support sustainable use of natural resource commons (Boyd et al. 2018; Moritz et al. 2018). Its 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 (Agrawal 2014). Research has shown that such arrangements usually include capacities for establishing locally meaningful rules or norms about what constitutes appropriate use of resources, for monitoring actors' actual resource use, for sanctioning violators, and for resolving disputes. These arrangements interact, with the consequence that a failure of one can lead to a failure of all and the consequent degradation of the resource system. But if structure is important, agency also matters. Local leaders, firms (Henderson 2020), other governance entrepreneurs (Andonova 2017), and boundary organizations (Fudge and Hiruy 2019) can all be important in enabling effective governance arrangements. States certainly continue to play powerful roles in preventing (or in some cases encouraging) overconsumption of natural resources, both through direct regulation and through providing forums for deliberation, support for information and monitoring activities, and as a backup for locally grounded sanctioning provisions (Mansbridge 2014). Finally, the general trend toward polycentric governance arrangements we noted earlier also turns out to be important for the particular case of collective action to manage natural resource commons (Andersson, Benavides, and León 2014). For example, hybrid arrangements integrating community and business actors have emerged as a promising trend in forest governance (Hajjar and Oldekop 2018). And scientists and multinational corporations have recently cooperated in advancing the sustainable development of seafood production (Österblom et al. 2017).

The newest chapters in the ongoing drama of the commons are currently being written through the growing application of network analysis (Bodin et al. 2019; Sayles et al. 2019) and complex adaptive systems modelling (Moritz et al. 2018; Schlüter et al. 2019). These approaches are clearly providing better explanations of how the intricate relationships among multiple actors, institutions, and action situations shape the great variety of polycentric governance arrangements now being used to guide the use of natural resource commons. Questions of power are also (if belatedly) being addressed (e.g., Morrison et al. 2019), a topic we explore in more detail below as part of our discussion of governance arrangements for advancing equity in sustainable development.

Difficulties, of course, remain (Quintana and Campbell 2019). 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. Such questions have long been a concern of governance scholars (e.g., Keohane and Ostrom 1995). But they have achieved special prominence in the context of global climate change, where Ostrom herself argued that a polycentric approach embodying much of what had been learned in the management of local commons should be substituted for the Hardin-esque monocentric governance arrangements embedded in the Kyoto

Protocol (Ostrom 2012). 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., Keohane and Victor 2016; Morrison 2017). These arrangements currently include patchworks of local initiatives, new norms for specific actors, recognition of co-benefits at local and global levels, national goals and reviews, coordinated international initiatives for research and monitoring and, of course, more traditional laws and treaties. A substantial body of research evaluating the determinants of effectiveness for these varied governance arrangements has begun to emerge. Recent work spans the gamut from formal international environmental agreements (Young 2018; Mitchell et al. 2020), through voluntary corporate standards for supply chain management (Lambin and Thorlakson 2018), to norm-driven initiatives to protect the global climate commons (Mitchell and Carpenter 2019) and the goal anchored efforts to achieve the UN's Sustainable Development Goals (Kanie and Biermann 2017). This research shows clearly that progress has been made in understanding how to guide the use of natural resources commons toward sustainability (e.g., Miteva, Loucks, and Pattanayak 2015). But shortfalls and outright failures remain the rule rather than the exception. The continuing lack of arrangements adequate to stem the continuing overconsumption of the earth's atmosphere (IPCC 2018), oceans (Hoegh-Guldberg, Northrop, and Lubchenco 2019), and biota (IPBES et al. 2019) are only the most discussed instances in which research shortfalls join institutional path dependence and the power of incumbents as barriers to governance reforms that could better nurture natural resources in the pursuit of sustainability.

8.2.1.2 Underproduction of anthropogenic resources

Governance arrangements for sustainability are also needed because individual actors underproduce certain resources that, if 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 nature 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., Ocampo 2016).

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 resources. A number of studies do examine how the pursuit of sustainability is affected by the availability of particular anthropogenic resources with high social value (e.g., educated people or innovative batteries). But for shared anthropogenic resources as a group, theorization and empirical work of the synthetic character we noted above for natural resources is virtually absent from the journals we have drawn on in the rest of this review. This neglect by the sustainability science community is only now, and slowly, beginning to be rectified.

The relevant research that does exist has identified many barriers to the provision or enhancement of anthropogenic resources with the potential for providing public value: free-riding as an institutional (not just market) failure, power asymmetries in transnational negotiations, the difficulties of accounting for linkages among action situations (sectors or

places), incompatibilities or competition among the resources themselves, and a path-dependent reluctance of existing governance systems to tackle new issues (Kaul 2012b; Anadon et al. 2016). Most of these barriers become higher as the level at which production occurs moves from the local to the national to regional and global.

Two basic forms of governance arrangements have been explored as means for overcoming these barriers. The first is financing, which may be provide provided through traditional direct investment, loans or aid, but also through prizes for innovation (Galasso, Mitchell, and Virag 2018; Murray et al. 2012). What makes some such financing interventions effective in producing socially valuable resources has long been studied by development researchers and is finally beginning to receive attention in the context of sustainability programs (Griffiths 2018). A second approach has been through treaties and analogous forms of cooperative agreements. These are also important and are increasingly being analyzed from a sustainability perspective (T. Liu and Kahn 2017). Much of the initial work on crafting such arrangements to provide anthropogenic resources needed for sustainable development focused on global public goods (e.g., essential medicines, agricultural research) and the role of powerful states or global collectives in supplying them (Kaul, Grunberg, and Stern 1999; Sandler 2004). More recently, scholars have begun to argue that truly global public goods have become increasingly difficult to provide, and that the action is properly shifting toward polycentric arrangements for producing resources that generate social value at local, national, and regional levels (Estevadeordal and Goodman 2017b).

8.2.1.3 Governing resources for sustainability?

There seems to be general agreement among researchers cited in this section that efforts to nurture resources for sustainability are more likely to be effective under governance arrangements which assure that actors with a stake in the outcomes can participate meaningfully in decisions about which resources are provided and who is involved in their production and distribution. Interactive engagement of this sort turns out to be important for at least three reasons (Dedeurwaerdere, Brousseau, and Siebenhüner 2012). First, it allows those seeking to promote the provision of anthropogenic resources to tap into users' existing knowledge and preferences. Second, it helps users to develop a more informed understanding of the joint private and public cobenefits that could be provided by enhancing particular resources. Finally, it enhances the legitimacy of the resulting governance arrangements.

Building from such general process guidance toward useful understanding of what specific interventions in publicly provided anthropogenic resources are most needed in what particular action situation is, however, proving to be enormously challenging (Burch et al. 2019). A central cause of these difficulties is almost certainly a lack of clarity on the part of researchers with regard to what governance of resources for sustainability is supposed to accomplish. Most work focuses on one or another of the 17 SDGs formalized by the UN. Relatively little attention has been paid by researchers to whether the resulting arrangements for guiding collective activity are likely to complement or compete with other efforts focused on other goals. Fortunately, while the SDGs may have failed to provide a toolkit for dealing with tradeoffs between goals, another part of the larger sustainability science research enterprise provides much needed clarity. Recall the research we reviewed in Section 3 that characterized a development pathway as sustainable if the social value (wealth) of its resource base—natural and anthropogenic—does not decrease. This

finding provides, in our view, a theory-grounded and practically useful answer to the question "Resource governance for what?" It should be adopted as one anchor for future governance research.

A second challenge to better resource governance is the continuing lack of any but the most basic accounts of what arrangements are actually in place around the world, and of evaluations that show how they are actually doing at nurturing resources for the pursuit of sustainability. As we discussed in Section 7, the ideal would be data sets and evaluations that reach comprehensively across instruments (e.g., cooperative agreements and financing), long time periods (e.g., generations), and levels of provision (i.e., local to global). The ideal remains almost as far off as it was a decade ago. But as we noted earlier, several efforts are now moving along for both the conservation of valuable natural resources (Mitchell et al. 2020) and the production of anthropogenic ones (T. Liu and Kahn 2017). They show feasible research pathways for the future.

The final challenge we address here for improving governance of resources is the lack of usable assessments about the likely future impacts of alternative interventions and arrangements. As noted in Section 7, such methods of linking knowledge with action to inform governance changes remain generally underdeveloped in sustainability science. Once again, however, some of the best work we noted there shows possible ways forward for natural resources (e.g., Jabbour and Flachsland 2017), anthropogenic ones (e.g., Conceição and Mendoza 2006), and even the two combined (e.g., R. D. Collins et al. 2017).

8.2.2 Promoting equity

Conserving the resource base is not the same as assuring equity in the distribution of the goods and services that flow from it (Agrawal 2014). Hence this second challenge of governance for sustainable development is to address issues of equity in both process and outcome: governance by whom (i.e., reflecting whose voices) and governance with what outcome (i.e., more or less equitable allocation of access to resources and the goods and services that flow from them) (Adger and Jordan 2009). Indeed, as we argue in Section 4, the desired outcomes of sustainability—including both intra and intergenerational well-being—are unlikely to be achieved without greater attention to and support for processes that take issues of equity, vulnerability, and social exclusion seriously and find ways to overcome the efforts of powerful actors to stymie transformations toward sustainability.

Inequity is reinforced by maldistributions of power, as we discussed in Section 4. Maldistributions of power are ubiquitous within current generations as a result of poverty or political marginalization and are particularly acute and difficult to remedy between current and future generations (Scoones 2009). Meeting sustainable development goals thus requires governance tools that assure greater intra and intergenerational equity. Governance tools to promote equity include: i) social norms and values; ii) laws, regulations, and rights; and iii) social movements.

8.2.2.1 Values and norms

Sustainable development, at its core, is a normative agenda that that emphasizes the values of well-being and equity for both current and future generations. Scholars have long recognized the

importance of changes in human values and behaviors to support sustainable development and ensure both intra and inter-generational equity. Leiserowitz, Kates, and Parris argue that "the achievement of long-term sustainability goals…will require an open, inclusive, and continuing global dialogue about what 'the good life' should look like, how to live it, and the values, attitudes, and behaviors, both individual and collective, that will support it" (Leiserowitz, Kates, and Parris 2006, 440). However, evidence supporting a causal relationship between purported sustainable values and substantive change in human behavior is limited (Peattie 2010). While individuals and groups may support abstract sustainable values including those of intra and intergenerational equity, individual actors make decisions constrained by both limited resources and competing goals. Both of these factors impede the translation of abstract values into actual behavior (Leiserowitz, Kates, and Parris 2006; O'Rourke and Lollo 2015). A particularly valuable extension of the work on values and sustainability has been the recognition that actors' empathy for nature and other people—a value often grounded in a sense of place and identity—can significantly influence pro-sustainability behaviors (Brown et al. 2019).

Behavioral economists and other scholars are activity pursing research agendas that encourage actors to overcome this attitude-behavior gap (O'Rourke and Lollo 2015). A well accepted conclusion of this research is that information provision about the negative impacts of individual behavior and consumption decisions alone is not an effective strategy for spurring sustainable behavior change. In place of closing the attitude-behavior gap, behavioral economists highlight the importance of default options and nudges that encourage pro-sustainable behavior (Bornemann 2019). However, nudges are only likely to take us so far towards more sustainable development pathways. The enormity of the sustainability challenge and the increasingly urgent need for rapid transformations in our consumption behaver have led to new and innovative approaches to encourage more sustainable decision making. For example, Bina Venkataraman, in her book *The Optimist's Telescope* tells the story of the NGO *Dear Tomorrow* which provides a platform for people to write letters to their future children. The process of crafting these letters creates imagined empathy for future generations. By making the well-being of future generations more salient to the letter writers, *Dear Tomorrow* and projects like it hope to help to close the attitude-behavior gap (Venkataraman 2019). Similarly, in their efforts to motivate today's decision makers, the growing global youth climate movement consistently highlights the impacts the climate change will have on the children and grandchildren of today's leaders in business and government (Farmer et al. 2019).

Perhaps the most promising role of norms and values in driving transformations toward more sustainable development pathways is through international norm-building efforts that activate new logics of appropriateness that can serve to guide international action (Mitchell and Carpenter 2019). Similar efforts to shift global values have led to changes in global governance in contexts as diverse as slavery, business, and human rights (Ruggie 2013), and costs for medicines to treat HIV/AIDS patients in sub-Saharan Africa (Moon 2019). Research is needed to help determine whether, and if so how, similar shifts in logics of appropriateness can change global norms with respect to the rights of future generations. The SDGs have had modest success in shifting global norms, but as discussed in Section 4 the SDGs still fail to seriously grapple with the well-being of future generations and tradeoffs between current and future generations. That said, focused research on the effectiveness of various norms for distributive fairness in motivating state action on climate change has argued for treating fairness as a multidimensional

construct and for mutual recognition of a limited range of legitimate norm interpretations (Underdal and Wei 2015).

8.2.2.2 Laws, rights, and regulations

Behavior change driven by sustainability values is unlikely to be sufficient to overcome the structural forces that underpin unsustainable development pathways. Even when individual actors or groups strive to align their behavior with sustainability, they face multiple barriers. First, it is often surprisingly unclear what is the sustainable choice or behavior in a given action situation—a special case of "wicked problem" characteristics typical of complex adaptive systems (Termeer, Dewulf, and Biesbroek 2019; Anderies et al. 2013). The greenwashing practices of unscrupulous firms that hope to capitalize on the sustainability values of their customers further reinforce this problem (Marquis, Toffel, and Zhou 2016). And more sustainable options are often not available to individual actors because the necessary infrastructure such as high-speed rail or more ambitiously passenger-grade solar airplanes has not yet been built.

Substantial structural change to assure equity for both current and future generations will almost certainly require further changes in laws, rights, and regulations. In the United States, the Clean Air Act (1963) and Clean Water Act (1972) are examples of early successes of the environmental movement to create legal and regulatory frameworks to promote sustainability. In recent years, sovereign wealth funds have played an increasingly important role in protecting the value of natural resources for future use not only in the wealthy nations typically associated with such funds but also in sub-Saharan Africa (Barbier 2019). Today, some of the most exciting developments in both theory and practice to empower future generations are taking place in the legal arena. The lawsuit *Juliana v. United States*, discussed in section 4, is grounded in the **Public Trust Doctrine (PTD)**[ll], a legal concept with roots in the common law of ancient Rome. PTD argues that certain natural resources cannot be fairly or effectively managed by private owners and that the government has a duty to hold these resources in trust on behalf of present and future citizens (Sagarin and Turnipseed 2012). While PTD law has a long history, its application to climate change is a new and evolving field of legal theory and practice. Nevertheless, a project run by the Sabin Center for Climate Change law at Columbia University has identified dozens of public trust claims on climate change in the United States, and an increasing number of claims in other countries including India, Pakistan, and Uganda (Sabin Center for Climate Change Law 2019).

Various rights-based and regulatory approaches to empower future generations are also being tested by governments and citizens around the world. Multiple countries including Hungary and Israel have appointed public guardians for future generations. 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 (Boston 2017). Rigorous evaluation of the effectiveness of such measures is, unsurprisingly, not yet available.

8.2.2.3 Social movements

The mutually reinforcing relationship between inequity and maldistributions of power discussed in Section 4 means that almost any effort to bring laws, regulations, rights, values, and norms that further the goals of sustainable development into widespread use will require strategies to overcome elite power and realign incumbent power structures (Sovacool and Brisbois 2019; Stirling 2019). Successful strategies of agitation against incumbent power structures by disempowered actors and their advocates usually involve some type of collective action in the form of social movements and other collective strategies of resistance (Scott 1985; D. J. Hess 2018). Indeed, social movements and other creative uses of the third dimension of power are one of the few tools that actors lacking the first and second dimensions of power have to ensure their voices are head in decision making processes and to reorient incumbent development pathways.

Social movements are "sustained and organized collective action to effect change in institutions by citizens…who are excluded from routine decision-making" (Amenta and Polletta 2019, 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 meso-level regimes. Social movements have diverse impacts on the trajectory of development pathways. Most frequently, the impacts of social movements are "fuzzy, contributing to something like a cultural zeitgeist in ways that are difficult to isolate" (Amenta and Polletta 2019, 292). But these fuzzy cultural shifts can have significant impacts on future of development pathways, by influencing what actions and behaviors that are considered socially appropriate or no longer acceptable. Changes in these 'logics of appropriateness' can eventually lead to more substantive changes in laws, rights, and regulations that have the potential to transition development pathways onto more sustainable trajectories (Bosi, Giugni, and Uba 2016).

Little is known about the effectiveness of different types of social movements for promoting sustainable development. One consistent finding is that effective social movements require not only collective action, but good strategy that mobilizes against all dimensions of power controlled by incumbent actors to reinforce their positions of dominance (Ganz 2009; McGee and Pettit 2019). However, more comparative research on social movements in pursuit of sustainable development over historical periods and across different kinds of action situations is needed to be able to offer more strategic advice linking different types of unsustainable incumbent regimes with effective social movement strategies.

Social movements and agitations against incumbent power structures are often bottom-up affairs. The importance of collective action and citizen participation in the success of development programs was has been recognized by the development community at least since the publication a generation ago of John Chamber's *Farmer First* (Chambers, Pacey, and Thrupp 1989; Mitchell and Carpenter 2019). The value of participation has led governments, donors, and development agencies to integrate participation into the design and implementation of governance processes and development programs. More recent work, however, questions blanket calls for participation (Bobbio 2019). Participation comes at significant cost to participants in terms of energy, effort, and time. So while promoting participation probably should remain one strategy for empowerment, it should be judiciously used under appropriate program designs that foster effective participation (Grillos 2019) and guard against government attempts to use nominal citizen participation as symbolic cover for continued business as usual activities (Dryzek et al. 2019).

8.2.3 Confronting uncertainty

The Anthropocene is characterized by deep uncertainty (Reyers et al. 2018). Scholars have made significant advances in understanding and modeling uncertainty in the Anthropocene System using methods developed for the analysis of complex adaptive systems (Johnson and Geldner 2019; Wiebe et al. 2018; National Academies of Sciences, Engineering and Medicine 2018; Shortridge and Zaitchik 2018; Polasky et al. 2011). Despite these advances, sustainability science has only a modest ability to predict future shocks and surprises, let alone steer the trajectory of development pathways over the multi-generational time-scales relevant to sustainability (Young 2017).

Three findings from the literature can improve the ability of governance arrangements to guide the Anthropocene System toward sustainability while confronting the deep uncertainty inherent in the system. The first is recognizing inherent tensions between governance arrangements designed to promote adaptiveness and governance arrangements designed to foster transformations. The need is to build governance arrangements that balance competing demands for adaptation and transformation. The second is understanding the ways in which anticipation and imagination drive development pathways, making some future sceneries more likely and others less likely. The need is to foster imaginaries that enable transformations to more sustainable development pathways. Finally, researchers' ability to predict future shocks and disruptions is imperfect. The need is to foster humble and reflexive governance arrangements that are able to question their own core commitments and incorporate diverse viewpoints, knowledges, and new information into decision-making processes.

8.2.3.1 Balancing governance for adaptation and governance for transitions

The first implication of the deep uncertainty of the Anthropocene System for governance arrangements is the need for adaptive capacity to respond to shocks and surprises. The research literature has produced a number of findings on how societies can do better with guiding adaptation pathways for sustainability. These include an array of expert-driven approaches to "adaptive management." More broadly, they address governance arrangements through which all actors (or their surrogates) can become empowered to advance their own conceptualizations of risks and adaptations, and through which all can participate in shaping adaptive pathways that promote a fair distribution of risks. The importance of adaptive capacity for sustainability is increasingly accepted by governance bodies and experts from local to global levels (Global Commission on Adaptation 2019; Flórez Bossio, Ford, and Labbé 2019).

That said, adaptation alone will not be enough to ensure sustainability. Where current development trajectories are already leading to declining inclusive wealth and where likely tipping points make critical regime shifts into unsustainable development pathways likely, sustainable development will require profound transformations onto alternative development pathways (Chapin et al. 2010; Linnér and Wibeck 2019). Accordingly, governance arrangements for sustainable development must find ways to nurture adaptive capacity while also fostering transformative capacity.

Designing governance arrangements capable of balancing adaptive and transformative capacity will not be easy. Indeed, while climate adaptation is now attracting the attention of corporate

interests who see myriad opportunities to profit from adaptation efforts (Slate 2019), efforts to promote more radical transformations still incite fierce opposition from the private sector (Folke et al. 2019; L. C. Stokes 2020). Empirical evidence also suggests that the governance arrangements for fostering adaptation are distinct from those best suited to foster transformations (Wilson et al. 2013) and that fostering adaptive capacities may even come at the expense of transformative capacities (Reyers et al. 2018; Marshall et al. 2012).

The governance challenge for sustainability is thus to design governance arrangements that are capable of supporting both adaptation and transformation and when necessary making appropriate compromises between the two governance strategies. Unfortunately, sustainability science to date has conducted limited research on what governance arrangements capable of achieving this balance should look like. Increased research to understand the adaption-transformation tradeoff is certainly needed. The good news is that insights from management and operations studies on long-term firm performance are applicable to this challenge. Firms routinely face strategic tradeoffs 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 (Tushman 2017; O'Reilly and Tushman 2008). Efforts to balance adaptation and transformation will likely require this kind of strategic thinking to overcome the biases of the individual actors and organizations deeply committed to one versus the other, and to evaluate which strategies are more likely to help guide the pursuit of sustainability in a given action situation. 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 Forum might accomplish this remains to be seen (Abbott and Bernstein 2015). And what analogous capacity is needed at other levels of governance has not, to our knowledge, yet been addressed by scholars.

8.2.3.2 Imagining sustainable futures

The second implication of the deep uncertainty facing efforts to guide the Anthropocene System involves the role of narratives and imagination. Research suggests that actors' behavior and decisions, especially with respect to choices about the future, are motivated less by accurate anticipations of the future, but rather more by collectively held narratives (J. Beckert and Bronk 2018). These collectively held narratives shape the behavior of multiple actors and are thus able to exert considerable influence over the trajectories of development pathways. Unsurprisingly, the power of incumbent actors is often predicated on their ability to craft narratives that engage citizen imaginations and limit the range of imagined futures to those that benefit themselves (see discussion of the 3rd dimension of power in Section 4). But while collectively held visions of the future—whatever their source—may push development trajectories along specific pathways, they often fail to envision shocks or surprises (J. Beckert and Bronk 2018). The blind spots created by such smooth narratives of the future create considerable resistance to timely action and exacerbate risks (Geiger and Antonacopoulou 2009).

The potential strength of narratives and collectively held imaginations of the future in shaping development pathways provides an important tool for the pursuit of sustainability. It allows agitators to craft narratives and create collectively held imaginaries of "The Future We Want" rather than just the ones we want to avoid (United Nations 2012). The Brundtland Commission report, in its optimistic assertion that "[h]umanity has the ability to make development sustainable," was an early effort to craft a sustainability imaginary. Even earlier, the Swedish government had commissioned a study by researchers and artists to portray visible landscapes under a range of energy development scenarios as input to its policy deliberations (UNESCO 1987; Emmelin 1996).[25] Later studies by the Great Transitions Project (Raskin 2016) and the Millennium Ecosystem Assessment (Carpenter, Bennett, and Peterson 2006) also made deliberate efforts to imagine alternative futures relevant to sustainability. More recently efforts to create new narratives of sustainability include efforts by proponents of the Green New Deal to link investments in greenhouse gas reduction with investments in green jobs and fairer economies (D. White 2019; Ocasio-Cortez 2019; Slobodian 2020).

While current governance arrangements for sustainability have become increasingly proficient in conducting anticipatory assessments such as the IPCC's emissions scenarios and Integrated Assessment Models (Vardy et al. 2017), it is not clear that the dominant governance arrangements currently in place are any good at imagining more sustainable futures or embedding those futures into collectively held imaginaries with the ability to drive change. Governance arrangements that provide opportunities for crafting narratives to guide transformations toward sustainable development pathways remain at the fringes of sustainability efforts (Pereira et al. 2018). Moving forward, governance arrangements for sustainability must improve their ability to craft narratives that influence the trajectory of development pathways in more sustainable directions.

8.2.3.3 Nurturing reflexive governance

One final implication of the deep uncertainty that characterizes the Anthropocene System is that governance and planning efforts to guide the Anthropocene System toward more sustainable development pathways must embrace this uncertainty (Anderies et al. 2013). If anything is to be learned from the history of development efforts in the 20th century it is that governance systems must learn to live with uncertainty rather than trying to manage or avoid it through tools of optimization and control (Hoekstra, Bredenhoff-Bijlsma, and Krol 2018; Scott 1998). Living with uncertainty means that governance arrangements must foster **reflexivity.**[mm] That is, they must cultivate the ability of governance arrangements to question their 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—confining development pathways to unsustainable trajectories (Dryzek and Pickering 2018).

Unfortunately, the pathologies of bureaucratic organizations at all levels from the local to global often make such reflexivity difficult (M. N. Barnett and Finnemore 2004). Fostering reflexive governance requires developing a set of "technologies of humility" which allow policy makers and other actors in and outside formal governance structures to systematically assess the

[25] An English language book with line drawings of many of the original watercolors is available (Emmelin and Brusewitz 1982), while color copies of some of the drawings are reproduced in Clark (1989).

unknown and uncertain futures. These assessments should pay particularly attention to four themes (Jasanoff 2005):

i) how problems and potential solutions are framed so as to ensure that neither alternate problems nor solutions are neglected;

ii) inclusion of viewpoints and histories of individuals and groups who are particularly vulnerable and whose viewpoints and well-being are often neglected in decision-making processes,

iii) attention to the distributional impacts of governance mechanisms including the design of both institutions and technologies with particular concern for the ways in which governance mechanisms impact the well-being of poor and vulnerable populations; and

iv) provide opportunities for collective learning and reflection to account for multiple viewpoints and avoid overly simplistic and monocausal assumptions about the variables and relationships undergirding development pathways in the Anthropocene System.

Research shows that reflexive governance arrangements benefit from tools of participation and deliberative democracy which engage diverse viewpoints to widen frames, raise concerns about distribution and vulnerability, and ensure continual learning (Dryzek et al. 2019). Reflexive governance arrangements must balance 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 (Stirling 2009), but no single model of reflexive governance will work in all action situations. Rather, efforts in sustainability science should strive to design governance frameworks that are as Dryzek and Pickering put it "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" (Dryzek and Pickering 2018, 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 (Young 2017).

9 CONCLUSIONS

We embarked on this review hoping to distill the core findings of sustainability science over the past 20 years and to identify the remaining questions. We found that the Anthropocene System is at its core a complex adaptive system that is inherently unpredictable and subject to deep uncertainty (J. Beckert and Bronk 2018; Reyers et al. 2018). Its current pathways of development are nonetheless almost certainly unsustainable and are held in place by inequality, emergent power structures, and incumbent regimes resistant to change (Stirling 2019). That said, the evidence shows that current pathways can sometimes be adapted and even transformed through informed intervention and, especially, innovation (Mazzucato 2018b). Steering inherently uncertain incumbent development pathways towards more a more sustainable trajectories is the defining challenge of our time.

Breaking out of the path-dependent ruts of existing development pathways will require more reflexive governance systems that are able to respond effectively to early warning signals of tipping points and regime collapse and to realign the institutional structures undergirding unsustainable trajectories toward more sustainable outcomes (Dryzek and Pickering 2018). Reflexive governance approaches can be strengthened by fostering the six capacities identified in

this review: 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 govern for sustainability. These capacities seem to interact with one another: if one is strong, it strengthens the others; if one is weak, the others are weakened with it. Cultivating them in parallel thus seems essential for the serious pursuit of sustainability.

The advantage of the capacities approaches is that society has not only already built a significant understanding of how to foster each of these capacities, but these capacities can be implemented today in governance systems across levels and between action situations. Moreover, these capacities can be aggressively fostered at the same time advocates for sustainability remain suitably humble and reflexive: recognizing that each capacity is probably necessary—but alone certainly not sufficient—to help guide the Anthropocene System toward sustainable development.

10 TABLES, FIGURES, AND BOXES

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12 DEFINITIONS USED IN THIS REVIEW

[a] **Anthropocene System**: The system marked by the increasingly global and intimate intertwining of nature and society.
[b] **Informed agitation**: The arousing of public concern about an issue for the purpose of bringing about action through the means of knowledge sharing, research, and deliberation.
[c] **Frameworks** provide checklists or building blocks of the elements and relationships among them that any research conducted within the framework ought to consider.
[d] **Elements** are variables or components of structure. They are coupled via relationships or functions.
[e] **Patterns** are observed or predicted distributions of the elements (variables) and relationships of interest, e.g., patterns of poverty, or of pollution.
[f] **Pathways of development:** Temporal changes in patterns of observed or predicted covariation in nature and society.
[g] **Well-being**: An integrating concept of the good life, the constituents of which will vary among people but may include health, security, community, the aesthetic appeal of flourishing environment, etc.
[h] **Power** is the ability or capacity of actors to affect the actions and beliefs of others.
[i] **Action situations** are domains or contexts of nature-society interactions in which particular actors, operating in particular institutional structures, make choices about using resources to achieve their goals.
[j] **Complex adaptive systems (CAS)** consist of interactions among diverse elements that give rise to novelty, patterns, and dynamics that feedback on those interactions, resulting in a continually evolving system.
[k] **Individuality** or diversity of actors and other elements means that their behavior cannot be understood in terms of averages.
[l] **Emergent properties** (emergence) arise from interaction of the parts of a system, but cannot be explained in terms of the "sum of the parts" alone (e.g., human health, traffic jams), i.e., the interaction of many autonomous individual components produces some kind of coherent behavior or pattern which is distinct from the autonomous behavior of the component parts.
[m] **Regimes:** A particular set of dominant relationships, feedbacks or other "rules of the game" (both natural and social) that give rise to characteristic dynamics and development pathways (e.g., fossil-fuel energy regimes, intensive agriculture regimes).
[n] **Threshold:** Condition at which small changes can have big effects, leading to qualitatively different regimes and pathways of development. Closely related terms are "tipping point" and "catastrophic bifurcation."
[o] **Capital assets**: Resource stocks—both natural and anthropogenic—on which society draws for its well-being (see Table 2).
[p] **Productive base**: The total set of resource stocks or capital assets on which society draws for its well-being.
[q] **Equity** refers to the qualities of justness, fairness, and impartiality, in contrast to **equality** which refers to sharing equal quantities of something.
[r] **Incumbency** (incumbent regimes): Relationships among actors and institutions through which power differentials shape, stabilize, and reinforce existing regimes and their associated development pathways.
[s] **Adaptation**: Response to potentially disruptive change that seeks to limit damage or seize opportunities for improvement.
[t] **Risk:** The prospect of loss or gain under uncertainty of something of thought to be of value, often incorporating estimates on likelihood of a change and consequences if the change occurs.
[u] **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.
[v] **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.
[w] **Innovation systems** consist of the actors, institutions, goals and resources through which new artifacts and practices are invented, selected, adapted, adopted, and brought into widespread use.
[x] **Disruptions**: Shocks, surprises, innovation, and the unfolding unknown.
[y] **Robustness**: A system's ability to absorb or otherwise cope with immediate disturbance without having its basic functions (e.g., support of well-being) irreversibly degraded.
[z] **Adaptive capacity** for sustainable development is the ability to harness robustness and resilience in ways that help in the pursuit of sustainability goals.

[aa] **Adaptation pathways**: Dynamical, and typically path-dependent, sequences of adaptations in which early adaptations influence the conditions that call for later adaptations.
[bb] **Hysteresis**: The tendency of a system change to be irreversible even when forces that caused the change are reversed.
[cc] **Transformation or transition** are large-scale and often disruptive shifts from unsustainable pathways of development to development pathways that (based on available data and understanding) are sustainable.
[dd] **Transformative capacity** for sustainable development is the ability to foster shifts across regime thresholds associated with development pathways resulting in declining human well-being and into alternative regimes in which human well-being is stable or increasing.
[ee] **Multi-level perspective (MLP)**: A hierarchical framework for analyzing innovation in socio-technical systems.
[ff] **Imaginaries** are collectively held visions of good or attainable futures that serve to envision the possible and motivate action towards new development pathways.
[gg] **Co-production**: Knowledge and society continually shape each other in a dynamic, path-dependent process.
[hh] **Safe spaces**: Institutional arrangements that encourage experimentation and the timely acknowledgment of error.
[ii] **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.
[jj] **Polycentric governance** involves multiple actors with partial authority interacting to create self-organized, multi-level arrangements for guiding collective behavior.
[kk] **Fit** is a term used to emphasize the importance of matching governance arrangements to the characteristics of the action situation being governed.
[ll] **Public Trust Doctrine (PTD)**: A legal concept that certain resources cannot be fairly or effectively managed by private owners and that the government has a duty to hold these resources in trust on behalf of present and future citizens.
[mm] **Reflexivity** is the ability to question one's own core commitments.