Global Environmental Change 39 (2016) 351–362

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Plausible and desirable futures in the Anthropocene: A new research agenda

Xuemei Bai[a,*], Sander van der Leeuw[b], Karen O'Brien[c], Frans Berkhout[d], Frank Biermann[e], Eduardo S. Brondizio[f,g], Christophe Cudennec[h], John Dearing[i], Anantha Duraiappah[j], Marion Glaser[k], Andrew Revkin[l], Will Steffen[m,n], James Syvitski[o,p]

[a] Fenner School of Environment and Society, Australian National University, Australia
[b] ASU-SFI Center for Biosocial Complex Systems, Arizona State University, USA
[c] Department of Sociology & Human Geography, University of Oslo, Norway
[d] Department of Geography, King's College, London, UK
[e] Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
[f] Department of Anthropology, Anthropological Center for Training and Research on Global Environmental Change (ACT), Indiana University, USA
[g] Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis, Indiana University, USA
[h] Agrocampus Ouest, INRA, UMR1069 SAS, Rennes, France
[i] Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK
[j] UNESCO Mahatma Gandhi Institute of Education for Peace and Sustainable Development (UNESCO MGIEP), India
[k] Leibniz Center for Tropical Marine Ecology (ZMT), Germany
[l] Pace Academy for Applied Environmental Studies, Pace University, USA
[m] Fenner School of Environment and Society, Australian National University, Australia
[n] Stockholm Resilience Centre, Stockholm University, Sweden
[o] Community Surface Dynamics Modeling System, University of Colorado-Boulder, USA
[p] International Geosphere-Biosphere Programme, Royal Swedish Academy of Sciences, Sweden

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 10 September 2015
Accepted 23 September 2015
Available online 24 October 2015

Keywords:
Anthropocene
Plausible and desirable futures
Societal goals
Societal trend and dynamics
Transition and transformation
Changing role of science

ABSTRACT

While the concept of the Anthropocene reflects the past and present nature, scale and magnitude of human impacts on the Earth System, its true significance lies in how it can be used to guide attitudes, choices, policies and actions that influence the future. Yet, to date much of the research on the Anthropocene has focused on interpreting past and present changes, while saying little about the future. Likewise, many futures studies have been insufficiently rooted in an understanding of past changes, in particular the long-term co-evolution of bio-physical and human systems. The Anthropocene perspective is one that encapsulates a world of intertwined drivers, complex dynamic structures, emergent phenomena and unintended consequences, manifest across different scales and within interlinked biophysical constraints and social conditions. In this paper we discuss the changing role of science and the theoretical, methodological and analytical challenges in considering futures of the Anthropocene. We present three broad groups of research questions on: (1) societal goals for the future; (2) major trends and dynamics that might favor or hinder them; (3) and factors that might propel or impede transformations towards desirable futures. Tackling these questions requires the development of novel approaches integrating natural and social sciences as well as the humanities beyond what is current today. We present three examples, one from each group of questions, illustrating how science might contribute to the identification of desirable and plausible futures and pave the way for transformations towards them. We argue that it is time for debates on the sustainability of the Anthropocene to focus on opportunities for realizing desirable and plausible futures.

1. Introduction

The concept "Anthropocene" was originally proposed as a geological epoch in which humans have become a dominant driver of Earth System change (Crutzen, 2002). In recent years, the use of the term has broadened to signify (1) the novelty of the time period

* Corresponding author at: Fenner School of Environment and Society, Frank Fenner Building, The Australian National University, Canberra 2601, Australia.
E-mail address: Xuemei.Bai@anu.edu.au (X. Bai).

http://dx.doi.org/10.1016/j.gloenvcha.2015.09.017

in which humans find themselves as a result of this; (2) the novel challenges, opportunities and uncertainties that awareness of global potency brings; and (3) the new perspectives required to deal with them. In the Anthropocene, change has reached the planetary level, not only through accumulation but also through the accelerating emergence of systemic symptoms of high magnitude and notable simultaneity and synchronicity (Steffen et al., 2015a). All aspects of these changes imply risk and security issues for nearer or more distant futures, from the unexpected magnitude of some processes to unperceived connections between them, to the crossing of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015b).

The Anthropocene encapsulates a world of intertwined drivers, complex dynamic structures, emergent phenomena, and unintended consequences, manifest across different scales of analysis and subject to multiple and linked biophysical and social constraints. Yet while the concept "Anthropocene" reflects the nature, scale and magnitude of human impacts on the Earth, its societal significance lies in how it can be used to explore and guide attitudes, choices, decisions and actions that will reverberate far into the future.

Exploring transformative changes towards sustainability has been identified as a key research challenge (Hackman and St Clair, 2012; Future Earth, 2014). Scenarios presented by the Millennium Ecosystem Assessment (2005) and by the Intergovernmental Panel on Climate Change (Allen et al., 2014) made it clear that the type and timing of human decisions and actions related to the global environment will influence future outcomes. Nonetheless, current mainstream thinking tends to revolve around "business as usual" futures that emphasize continuity and predictability based on known patterns of change, rather than focusing on potential discontinuities, emergent patterns of change and plausible and desirable futures futures.

Human influence on the Earth System has been ongoing for centuries (Turner et al., 1990), yet only recently has it had significant implications for the structure and functioning of the Earth System at the planetary level (Steffen et al., 2015b). In the Anthropocene, humans are doing more than simply changing local land cover, extracting resources, and degrading the air, water, and soil. They have also become key drivers and amplifiers of planetary change, influencing large-scale processes and systems, including the climate, the oceans and terrestrial ecosystems, and ultimately the functioning of the Earth System as a whole. These intertwined and more complex socio-ecological systems are likely to exhibit more unexpected, emergent behaviors, with new risks and uncertainties. However, despite deep and irreducible uncertainty, the notion of the Anthropocene explicitly acknowledges the role of humans in the transformation of these social–ecological systems, and recognizes that human agency will play a key role in the future.

The Anthropocene thus implies a fundamental reconceptualization of the role of individual and collective human agency and its relation to structures, systems and inputs. It requires raising or reexamining many important normative, philosophical and empirical questions about human agency, as well as discussing expectations and normative positions concerning the future: "How can we express a collective responsibility for our future?", "Is there a new volition for defining planetary futures?", "What kind of future do we want?", "Is it possible to agree on global development pathways for the Earth system?", "Who decides?", "Are connected yet divided cultures and societies up to the challenge of working towards shared goals?", and "How can the sciences contribute to meet the challenges involved?"

Answering such questions places a premium on the ability of people to produce and use the knowledge needed to define and influence trajectories of planetary development. This involves understanding not only current patterns of first and second order change in systems, but also the dynamics of non-linear and emergent future changes. Limitations in human information processing suggest the need for a careful, precautionary approach in dealing with Anthropocene challenges, for example regarding proposals for large-scale geo-engineering experiments (Hamilton, 2013). But levels of precaution themselves are subjective and variable, and a function of culture, capacity and history (Silva and Jenkins-Smith, 2007).

In this paper we discuss some of the scientific challenges of looking into futures, and we present a research agenda for a new way of engaging with Anthropocene futures. Our point of departure is a recognized need for collective reflection on plausible and desirable futures in the Anthropocene. We consider desirable futures those futures that improve the chances for our societies to surmount the current crises, which are influenced by disparate human values and aspirations. Plausible futures are broader range of possible futures, which depend on understandings and assumptions about planetary change. We argue that sustainability debates should focus less on the continuity of present pathways and be more inclusive of new visions and opportunities offered by desirable and plausible futures, opening up a wider range of 'outside-the-box' possibilities as well as new ways to achieve them.

Our vision of the emerging research agenda is organized around three broad groups of research questions, namely (1) societal goals, (2) major trends and dynamics, and (3) transition and transformation towards desirable futures. Fig. 1 presents our conceptualization of the relationship between these components. In Section 2, we discuss some of the general, theoretical and methodological challenges of looking into futures. Section 3 then focuses on building the research agenda around the above identified three topics, with specific research questions embedded in the reviews of current literature. In Section 4, three innovative approaches in addressing some of these questions are discussed by way of examples. Section 5 presents the conclusions.

2. Scientific challenges of looking into futures

Navigating the Anthropocene requires a systematic thinking about the future, as both drivers and consequences (intended, unintended, and unanticipated) of societal actions accelerate and amplify, moving clearly away from a sustainable end. Forecasting the future with any level of consensus and/or reliability is difficult because forecasting entails error, and the future is an emergent property shaped by individual and collective choices, decisions and actions at all levels, and influenced by biophysical constraints. There are at least three challenges in terms of looking into Anthropocene futures.

First, the complexity and uncertainties of the Anthropocene encounter the cognitive limits of human beings. Most modern humans can individually integrate a limited number of sources of information (or dimensions of a problem) simultaneously (Read and van der Leeuw, 2008), although recent research on neuroplasticity shows that these characteristics are dynamic. The implications of this limitation differ, depending on whether people are describing causal explanations for the present or predicting the outcome of observed processes in the future. When considering past processes with known outcomes, narratives can be created by drawing on a limited number of relevant dimensions of past processes and making a plausible case for what led to the experienced outcomes. But when considering the future, there is no single outcome that can serve as a focus for a narrative, and the best that can be done is to create multiple narratives (scenarios), each invoking different dimensions, none of which will entirely 'predict' what will happen. Probabilities, contingencies,

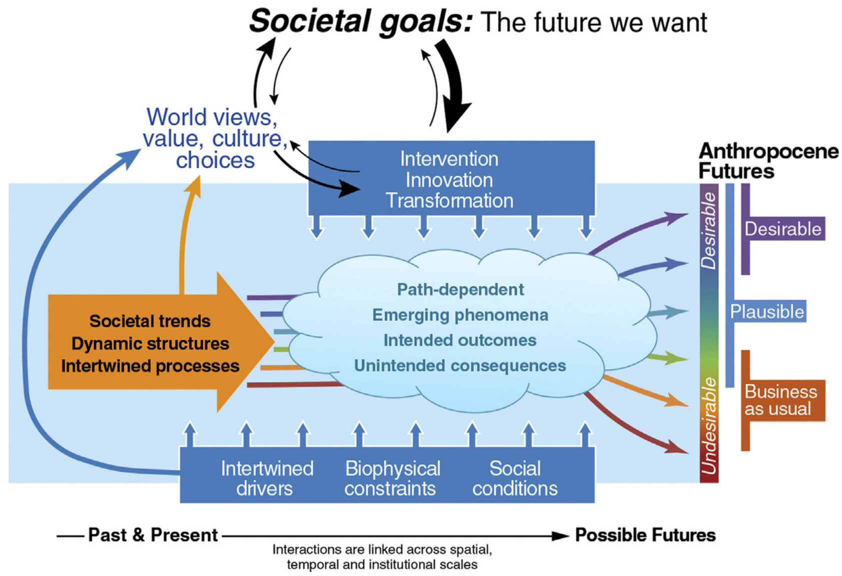

Fig. 1. Conceptualization of the inter-linkages between factors and dynamic processes shaping the Anthropocene futures.

conditionalities and thresholds need to be assigned to them as a measure of the extent to which scenarios seem 'realistic'.

Second, the need for ever more precise communication among large numbers of people (including scientists) has led to a proliferation of ever 'narrower' concepts (categories) at any particular level of abstraction. This reduced the number of dimensions in which concepts could be interpreted, avoiding misunderstandings and errors. Yet it also contributed to the fragmentation of scientific perception, the hyper-specialization of scientific disciplines and the difficulty of developing a coherent and multi-dimensional vision of the future. While a disciplinary and reductionist approach is essential in advancing science, it has proven to be insufficient to address complex societal issues with unclear system boundaries, multiple interactions across natural and social systems, different temporal and spatial scales, and deep influences by human values, behavior, culture and institutions. Inter- and trans-disciplinary approaches are increasingly called for, yet they remain to be fully integrated into the institutional settings of research, funding and education. Indeed, many barriers to future-oriented thinking are inherent in the disciplinary organization of the scientific enterprise, including financial and organizational barriers to such efforts.

Third, once a scenario/narrative/vision has been developed, social actors may respond to this with actions that would not have been taken in their absence. Through constructive shared reflection on a possible future, the actual trajectory might be altered, even though current climate change governance reveals the difficulties in achieving such changes in trajectory. Although difficult, such reflexivity introduces important opportunities, both for shifting away from catastrophic future scenarios (Young et al., 2006), and for creating desirable novel futures.

Faced with these three challenges, it is important to transcend the relative incapacity of science to focus on the future (van der Leeuw et al., 2012). Science as it has been practiced over the last couple of centuries (in the form of hypothesis testing, problem solving and learning strategies through trial and error) has not kept up with the rapid and accelerating social and biophysical changes. To understand and shape potential futures, we need to study emergence and *feed-forward* processes and develop a perspective that can handle increasing complexity. This requires a fundamentally different way of practicing science, where the current 'ex post' or 'after the fact' perspective that focuses on learning from the past about the present and extrapolates this to the future is expanded to include an 'ex ante' or 'before the fact' perspective that learns from the past about the present *for the future*. The latter perspective studies the *emergence* of novelty rather than its origins. This 'Complex (Adaptive) Systems' approach (Mitchell, 2009) is becoming more common, particularly in the natural and life sciences but also in the social sciences (Urry, 2005). To develop a comprehensive perspective on plausible and desirable futures and as well a road map for realizing it, complex systems thinking needs to be fully integrated into sustainability research.

Removing barriers in thinking about the future will be important but challenging. Modernist tendencies to subdue cultural differences, conquer nature, remove limits, promote economic growth and support the expansion of science and technology have not disappeared (Slaughter, 2002). Uniformitarian assumptions have been the basis for the understanding of past changes, and have also served to formalize the analysis of future changes. The scientific community needs to learn how to negotiate trans-disciplinary "question setting" and to develop collaborative skills around issue-, problem- or solution-oriented research among scientists and with stakeholders in civil society. Novel methods and techniques of data gathering, analysis and synthesis must be identified that enable integration so that a holistic approach will emerge. Current scientific practice and organization does not necessarily support such approaches, and fundamental changes that encourage teamwork, multi-dimensional and multi-cultural discussions, reflexively considering alternatives, are essential. Transformation of the education system, including the training of educators, is needed to encourage teaching and research on issues of high societal and future relevance.

One methodological challenge that deserves particular attention is that of combining abstract, theoretical and systemic knowledge with contextual and place-based understandings. While equation-based, top-down systems modelling can simulate major trends and scenarios but poorly linked, bottom up modelling focuses on "agents" with potentials for altering the future (Verburg et al., 2015; Glaser and Glaeser, 2014). The recognition of individuals as active agents in a social–ecological system opens up a range of such options. For instance, an understanding of institutions as emergent from the multiple interactions of goal-oriented system actors shows how individuals shape institutions, and how institutions influence individuals (van der Leeuw, 2012). Such models are mostly located at lower local and regional system levels and thus require up-scaling or nesting within larger bio-geophysical models (Kroeze et al., 2008).

3. Towards a research agenda for the Anthropocene

As presented in Fig. 1, Anthropocene futures are dependent on many processes and interactions. We consider the following three questions as essential to exploring Anthropocene futures: "What are the futures that we want?", "Where are the current trends and tendencies leading?" and "How do we transform towards desirable futures?". The following subsections explore these questions in detail, presenting a review of current knowledge and posing specific research questions relevant to each of them.

3.1. Societal goals: what are the futures that we want?

The future is defined as something that exists or occurs at a later time, which includes both near-term and long-term aspects, including "deep time" futures that occur over geological time-scales. Within the field of futures studies, attention is often paid to the long-term, which is beyond the scope of 5–10 year strategic and operational planning. The most common approach to the future is to develop scenarios or storylines that project different outcomes based on assumptions and perceived relationships. Foresight methodologies often draw on social constructionist approaches to produce instrumental knowledge related to a future time, recognizing that knowledge, meaning and action are continually produced and reproduced through human interactions (Fuller and Loogma, 2009). Visioning approaches are common, where visions are often seen in relation to an ideal or positive future, based on the assumption that a vision is necessary to coordinate actions in a desired direction (Van der Helm, 2009). Miller (2007) argues that an exclusive reliance on prospective and/or value-based future scenarios can lead to incomplete and inadequate understanding of the full potential of the present to generate alternative futures.

Limits to Growth (Meadows et al., 1972) was the first study to systematically explore and develop future scenarios of human society, resource and environment interactions through world system dynamics modelling. A review of these model results after 30-years indicates that society had largely followed the "business as usual" scenario, which predicted a collapse in social–ecological systems by mid-21st century (Turner, 2008). With the recognition of humans as the dominant force shaping biological systems (Vitousek et al., 1997; Palumbi, 2001), there is a shared understanding of the need for a different future, and a greater effort devoted to developing future scenarios through a better understanding of the past (van der Leeuw et al., 2011). But how to reimagine and create novel futures that drastically depart from past trajectories remains a challenge (Costanza and Kubiszewski, 2014). Moreover, the drawbacks of future projections, as Miller also points out, include the risk of using methods and models that draw on what happened in the past: "Yesterday's parameters may do a good job at tracking past events, but experience shows that this approach consistently misses major inflection points related to long-run transformative changes" (Miller, 2007, p. 342). This is partly because the parameters for judging the performance of systems themselves will change. Systems may also change their structure, i.e. their functional architecture of parameters. There is also the risk, Miller argues, that " . . . a preoccupation with what is likely to happen tends to obscure outcomes that may be unlikely but still possible and potentially more desirable" (ibid).

Perceptions of risk clearly influence approaches to the future, thus understandings of how humans are shaping future risks and outcomes takes on added significance in the Anthropocene. There is a large body of research on risk perception, risk analysis and decision-making that identifies heuristics describing how individuals understand and respond to risk (Slovic et al., 2004). Since the 1980s, concerns over social perception and reactions to risk gained attention in the social sciences, not least as part of increasing interest of the social sciences in the rise of environmentalism. Anthropologist Mary Douglas and political scientist Aaron Wildavsky called attention to how societies prioritize the perception of and attention to danger based on social construction of risk and imperfect or selected knowledge (Douglas and Wildavsky, 1983), in other words, how social principles define the types of dangers to which societies pay attention. Sociologists such as U. Beck and A. Giddens have called attention to the emergence of 'risk societies' rooted in the growing concerns about the crisis and vulnerabilities to disaster (Beck, 1992). Having environmental risks at the center, they portray modern societies as increasingly concerned with anticipating the future. In different ways, they call attention to the importance of both persistent and new social structures to maintain differential abilities to anticipate and respond to risk across different sectors and strata of society.

More recent approaches to risk in the Anthropocene recognize the fundamental contribution of humans to risks that have increasing costs to society. Kasperson et al. (1988) have very early emphasized the social amplification of risk, while Renn and others have been concerned with developing ways to govern uncertainty and risk (Jaeger et al., 2001; Renn, 2008). One of the important shifts here is from an approach that sees people as responding to natural hazards and risks to one that looks at risks as emerging from socio-environmental interactions (Renn, 2014). Helbing (2013) has recently emphasized how, in the Anthropocene, risks are moving from a local or regional scale to a global one, highlighting some of the consequences of that shift, and Jaeger et al. (2013) are emphasizing the need for a global approach to these issues under the banner "Global Systems Science". More and more emphasis is also given to risk cascades, including technological risks (e.g. Tainter and Patzek, 2011), that incorporate Complex Systems ideas. Important questions remain: "Are the risks and uncertainties amplified in the Anthropocene?", "Are the shifts discussed above effective or sufficient in addressing these risks and uncertainties?", "Can the society perceive and prepare for the deep uncertainties that are considered immeasurable and beyond calculation, e.g. the Knightian uncertainties (Knight, 2012)?", and "How are such perceptions formed, and how do the different perceptions affect the decision making and behavior?"

Evidence shows that human perception and cognition have a clear role in the risk perception, the subsequent decision-making, and behavior. Kahnemann et al.'s work on decision making under uncertainty revealed asymmetrical impact of question framing on cognition (Kahnemann et al., 1982; Tversky and Kahnemann, 1981), the errors that arise from heuristics and biases (Tversky and Kahnemann, 1974), and the importance of "bounded rationality". Other research has emphasized the contextuality of perception and cognition, and therefore of decision making (Bowles et al., 2004). Comparative experimental research between individuals embedded in Western and Eastern backgrounds has emphasized that different cultures may view the relationship between subject and context differently, with important consequences for the outcome (Nisbett, 2003). Ostrom (1990) has based her analytical IAD approach on the fact that decisions are impacted by the actual material and social situation in which they are made, including the personalities involved. Janssen et al. (2014) have highlighted the impact of different modes of communication between participants on the decisions made both experimentally and through the use of

Agent-Based Models. These are just some examples of a research area of great importance, to which we must pay attention in studying the Anthropocene if we are to build a solid understanding of environmental decision-making.

Another important question to ask is how to address the vast disparities within human society in the discussions and decisions about desirable future development paths. Approximately 1.1 billion people have no safe drinking water; 2.6 billion remain without adequate sanitation (WHO, 2015). Roughly one in eight individuals lacks sufficient food, and 25% have no access to electricity (United Nations, 2013). On the other hand, roughly 1000 individuals (the world's billionaires) have more assets at their disposal than the entire gross domestic product of India or the African continent (Hay, 2013). Values, perceptions and aspirations of people are highly diverse, and power and self-interests make collective decisions about any planetary future highly difficult. This calls for an improved understanding and recognition of the underlying values, interests, contradictions and power related to human and planetary well-being, along with more research and debate on theories of global and local justice (Sen, 2011; Biermann, 2014; Biermann et al., 2016).

In that context, another critical question arises: Who will eventually make decisions on future development paths (Castree et al., 2014)? Will future development paths be determined more through conscious consensus-based or majority decisions, predominantly guided by governmental policies and strategies as demonstrated by national policies on urbanization in China (Bai et al., 2014), or more likely emerge through indecision, through sustained dynamic push-pull relationships at different scales among sectors of societies and groups of nations? We would argue that instances of all will occur, as well as examples of yet other ways to arrive at decisions. Given their vast differences in values, economies and conceptions of well-being, nation states are likely to continue to offer fundamentally different views on the directions to take, and the costs that each country should bear. The difficult negotiations in world trade or climate policy are examples of national interests dominating over global interests. Although the UNFCCC goal of limiting global warming to 2 °C shows that setting global targets may be possible (even though the implementation in political practice is lagging), it remains an open question whether such targets can be set in other domains (Rockström et al., 2009; Steffen et al., 2015b).

What does all this mean for governance for the future? Some observers call for strengthened institutions for effective Earth system governance and multilateral decision-making, for example, through a wider use of majority voting in international negotiations that would speed up decision-making (at present, about 70% of multilateral environmental agreements rely on consensus-based decision-making, requiring support of all governments) (Biermann, 2014). Others point to novel modes of multi-level governance, including engagement of civil society, global alliances of cities, or transnational partnerships that bring together businesses and NGOs (Ostrom, 2010; Cole, 2015). While the option of strengthening multilateral institutions faces many difficulties, the second option still raises questions about its overall feasibility and effectiveness—will a decentralized system of private and subnational initiatives be sufficient to resolve problems at the global scale? How will common goals and objectives be set? How will coordination and effort-sharing be achieved? To what extent are our scenarios of future trajectories influenced by current built-in policies and power structures? Until these issues have been settled, we will not go far and fast enough to be able to adapt to any future scenario.

Some progress may be made by reconsidering the ways in which decision-making issues and questions are framed. Thus far, in the UNFCC negotiations, the issue has been framed as one of burden sharing, leading to opposing views between the developed and the developing nations. Were we to reformulate the issue in terms of creating opportunities for technological, economic and social development (cf. Zhang and Shi, 2013; Jaeger et al., 2012), focusing on desirable futures in other words, that opposition would almost certainly lose much of its edge, as all nations would see development as a positive goal whereas they see burden sharing in a negative light.

A recent example of global goal-setting is the set of Sustainable Development Goals, currently being negotiated within the UN system. Should Earth System boundaries, from climate change to freshwater use, be addressed through independent, stand-alone goals? Or should Earth System constraints rather be integrated into all other goals, such as those on health, food, water, and education (Biermann, 2012; Griggs et al., 2013)? How can these goals be communicated within wider society? How are different aspects of the goals related, and what trade-offs exist? Can we maximize all ecosystem services, for example, water, energy, and food for all? If not, how can we optimize and include justice and equity in the distribution of wellbeing into our goals? What are the natural and social limits and boundaries, and how do they interact with each other (Rockström et al., 2009; Raworth, 2012; Steffen et al., 2015b)? Because these are open questions, they suggest the need to adopt a fundamentally open-ended way of thinking about futures in the Anthropocene, and to build in adaptability and feedback and reiterative processes that enable us to continuously adjust our goals.

3.2. Where are we heading: major trends and societal dynamics of the Anthropocene

A key question to address is achieving better understanding of the major trends and dynamics of society and the environment across all scales, as these trends and societal dynamics influence and shape future development pathways. Specific research questions would include: “What are the key societal trends and drivers?”, “How these trends and drivers interact and intertwine with each other?”, “How the dynamics of the Anthropocene, including a growing role of human agency in relation to Earth system processes, influence theories of social change and approaches to the future?”.

One of the most common representations of the major trends in the Anthropocene, both the underlying social dynamics and their impacts on the Earth System, is a representative set of 24 globally aggregated trends (12 socio-economic; 12 Earth System) from 1750 to 2000 (Steffen et al., 2015a) (Fig. 2). The graphs show the striking coupling between human activities and changing values of indicators of Earth System structure and functioning since 1950. This coupling is backed up by strong evidence that, in every one of the 12 Earth System graphs, human pressures are the primary driving forces for the observed trends (Millennium Ecosystem Assessment, 2005; Steffen et al., 2015a, 2007; Rockström et al., 2009; Syvitski and Kettner, 2011; Stocker et al., 2013). The sharp increase in human activity from the mid-20th century onwards stands out clearly, prompting use of the term “Great Acceleration” to describe this post-1950 phenomenon (Steffen et al., 2007). These trends, and the underlying science and observations behind them, provide the most coherent body of evidence for the Anthropocene as a new geological epoch in Earth history (Zalasiewicz et al., 2014).

The 12 Earth System trends of the Great Acceleration clearly show that societal responses must increasingly consider the global-scale consequences of cumulative local actions. Several of the processes involved are global by nature – climate change, stratospheric ozone depletion, ocean acidification – while others are local/regional in nature but can aggregate to generate global-

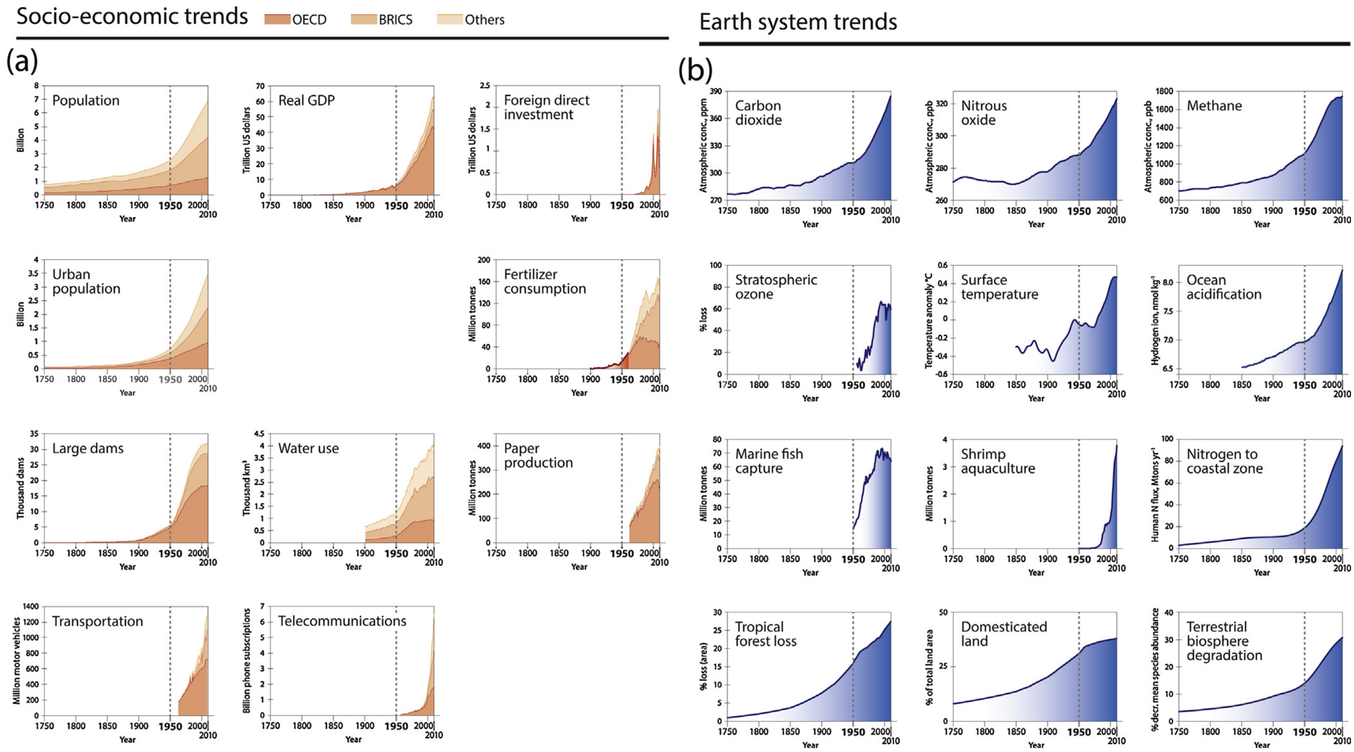

Fig. 2. (a and b) Earth system and socio-economic trends.

Source: Steffen et al. (2015a,b).

level emerging consequences, as shown by Hughes et al. (2013) and by recent research on the phosphorus cycle (Carpenter and Bennett, 2011) and the nitrogen cycle (de Vries et al., 2013; Sutton et al., 2013).

Where the data permit, these 12 socio-economic trends are split into contributions from the wealthy (OECD) countries, five large countries with emerging economics (Brazil, Russia, India, China, South Africa), and the rest of the world. The splits show (i) the great differentials in the causation of the Anthropocene since the beginning of the Great Acceleration and the inequities in sharing its benefits, but also (ii) the possibility for technological leapfrogging (e.g., telecommunication devices) for meeting critical development needs while simultaneously taking pressure off the Earth System. If the BRICS and the developing countries were to reach, as may be expected, the same level of economic development and wealth as the developed ones, how would that affect the Earth System?

Many of the Great Acceleration trends have both positive and negative aspects. For example, humanity has built one large (45 m or higher) dam every day for the last 140 years, at an accelerating pace. The cumulative effect has fundamentally changed the plumbing of the world's waterways and rivers. Dams offer environmental advantages (e.g. supply of hydroelectric renewable energy, clean water supply for agriculture, industry and our cities) and disadvantages (e.g. sediment trapping helping to accelerate delta subsidence, saline intrusion and increases in deltaic soil salinity, biodiversity loss in coastal wetlands) (Vorosmarty et al., 2010; Syvitski and Kettner, 2011; Montanari et al., 2013). Do the advantages outweigh the disadvantages? Who are the winners and who are the losers?

Similar two-sided stories are increasing in number and in the magnitude of their consequences. Shrimp farming on deltas, for example, is clearing mangrove and replacing rice farming (Barbier and Sathirathai, 2004; Lebel et al., 2002). A local shrimp farmer can greatly increase his income, and provide much more protein per hectare than through traditional rice cultivation. But the pumping of groundwater may cause the delta to subside more rapidly, suggesting that the current shrimp farming approach may not be sustainable. Fish farms on the Yellow River delta (Higgins et al., 2013), for example, are causing local subsidence at one meter every four years. These – and similar – examples raise a series of questions: “How will the consequences of such trends at local level impact on the future of the Earth System?”, “Can local or global solutions to address these impacts be found?”, “What are the unintended, new problems these solutions are likely to entail?”, “Can these be predicted as the Earth System moves out of equilibrium?”.

Understanding the social dynamics behind such trends requires attention to the complex nature of regional social–ecological systems. A promising approach seeks to obtain a deep understanding of contemporary system functioning. Particularly important is observing trends through time and understanding the co-evolving relationships between different drivers and response variables at different scales (Dearing et al., 2012). Findings from eastern China (Zhang et al., 2015) show a local trade-off between economic growth and accelerating losses of regulating ecosystem services in rural landscapes over many decades, which together are now threatening the future of many farming communities. At national level, studies show there are positive feedback relationships between the landscape urbanization and economic growth in China, and understanding such complex relationships has important policy implications (Bai et al., 2011).

These approaches require that the planetary boundaries concept be downscaled to regions. Safe and just operating spaces for regional social–ecological systems (Dearing et al., 2014) are defined within a complex systems framework as the margin between the sustainable use of ecosystem processes and services, the so-called ‘environmental ceiling’, and the minimum expected social norms, the so-called 'social foundation'. This approach offers a management tool for avoiding unsustainable ecological paths in economic development. The question remains as to whether and how these global and regional approaches can contribute to structural changes, transitions and transformations to desirable futures.

3.3. Transition and transformation towards desirable futures

To move towards a desirable future in the Anthropocene, there have been increasing calls for wide-ranging structural change and social transformations that are both ethical and equitable, drawing attention to a diversity of philosophical, social, cultural and biological theories and approaches to human agency and the potential for individual and collective change (Berkhout, 2002; Beddoe et al., 2009; Chapin et al., 2009; O'Brien et al., 2009; Biermann et al., 2012; Allen et al., 2014).

As we laid out in previous sections, research has shown that there are plausible, diverse scenarios that remain within Earth's safe biophysical operating space and achieve a variety of development targets. However, " . . . dramatic social and technological changes are required to avert the social–ecological risks of a conventional development trajectory" (Gerst et al., 2013). A number of interlinked transitions have been identified as being central to increased sustainability: demographic, technological, economic, social, institutional, informational and ideological (Gell-Mann, 2010).

It is important to recognize that many of the dominant ideas and narratives about development and progress today rest on assumptions about social complexity and change developed during the 19th and 20th centuries. Models of social change (and their critiques) and concerns about how societies transition from simple to complex social arrangements formed the foundation of social theory during the 20th century (e.g. Polyani, 1944; Steward, 1955; Rostow, 1990). Many of these are still influential today. They assume that stable equilibria are the norm for societies, and that structural changes occur intermittently and have to be explained, often by invoking some kind of external perturbation. They also drew on the idea of continuing progress from the simple to the more complex without taking the possibility of regression into account.

Recent conceptual frameworks, models and theories of social and biophysical transitions, drawing on Complex Systems approaches, have emphasized multi-scale or multi-level dynamic explanations (Holling and Gunderson, 2002; Geels, 2002; Carpenter and Bennett, 2011) that open the door to considering internal dynamics as drivers of both stability and change, of increasing as well as decreasing complexity. Within these frameworks, the underlying order in a system is typically conferred from higher levels of the system, but this depends on the reproduction of actors, networks, beliefs and behaviors at lower levels. For instance, in a multi-level perspective of socio-technical systems (Rip and Kemp, 1998; Geels, 2002), order is sustained within regimes by technological, cognitive and institutional factors that tend to exclude alternatives, supported by stable social, cultural and constitutional factors operating at a landscape level. Structural change may come about when radically novel alternatives emerge from small-scale niches and experiments, but only at times when a dominant and stable regime becomes vulnerable, for example, when it faces fundamental problems of resources or legitimacy. During these periods the regime loses coherence, and novel alternatives may come to reconfigure the socio-technical regime.

Other theories of structural change build on different mechanisms, but they all tend to be systemic in approach and concerned with cross-scale interactions and the dampening or propagation of changes in relationships between elements of systems. Such changes in interactions lead to changes in the functioning, organization and structure of the system. In social and technical systems the role of novel elements, and especially of innovations and new technologies, are highlighted in this process of the reconfiguration. But there is increasing recognition that new technologies are shaped by and come to shape social relations and practices. How social–technical innovations emerge, how to initiate and upscale purposeful changes that deliver sustainability outcomes, and how to extract knowledge and learning from successful processes remain as important research questions.

Structural change may be seen as an emergent property at the system level, with the set of causal relationships that unfold in a process of such change too complicated to be fully captured in any single analytical frame, therefore it may be difficult to envision or predict. As such, natural and the social sciences have been overly cautious about predicting such system transformations, and are generally too reticent about making firm recommendations on actions that would lead to transformation.

Different understandings of human agency and its relationship to structures can lead to contradictory and competing views of the potential for individuals and collectives to engage consciously with system change. A materialist approach to transformations tends to place emphasis on changes in behaviors, with little attention to subjectivity and the social construction of knowledge, and little recognition of contributions of the interpretive social sciences and humanities towards understanding social transformations in the Anthropocene (Castree et al., 2014). Nonetheless, human action affects many more dimensions of the Earth system than are recognized by the actors (Steffen et al., 2015b). This dimensional asymmetry means actions will almost always entail unintended consequences. Moreover, in their interaction with the environment societies transform the 'risk spectrum' of the social–ecological system, replacing known shorter-term risks with a wide range of unknown longer-term risks (van der Leeuw, 2012).

Reconciling diverse understandings of humanity's role in, and relationship to, the Anthropocene may thus be difficult. Transformations to plausible and desirable futures call for more than greater expertise, knowledge, and know-how for system level re-design and management for a sustainable future (Beddoe et al., 2009). Instead, such transformations can be seen as an adaptive challenge that draws attention not only to technical aspects of the problem, but also to beliefs, assumptions, values and worldviews that contribute to different understandings of human-environment relationships, as well as to different views of "structures" and "systems" (O'Brien and Selboe, 2015). The human capacity to perceive and respond to the collective challenges of the Anthropocene through deliberate transitions and transformations requires renewed attention to and innovations in theories of social change.

There are nonetheless entry points for effecting transformations in systems, as described by Meadows (1999). Her leverage points for systems change range from changes in parameters and numbers, and in stocks, flows and feedbacks (lower leverage) to changes in goals and paradigms (higher leverage). The research focus has started to shift from revealing alarming signals for the future towards exploring alternative, more desirable futures through transition (Raskin et al., 2002; Kates and Parris, 2003) and transformation (Rees, 1995; Folke et al., 2002; Berkhout et al., 2004; Haberl et al., 2011; Westley et al., 2011; O'Brien, 2012; Hackmann and St Clair, 2013) to implement the fundamental changes that society needs to go through to achieve sustainability goals. Recognizing the importance of shared visions and goals, the narratives in international assessment and policy forums also changed—from exploring plausible future scenarios with different outcomes for different parts of global society (e.g. Millennium Ecosystem Assessment, 2005) to attempting to identify common societal visions, as illustrated in the Rio+20 declaration "The Future We Want" (UN General Assembly, 2012). However, as discussed above, futures will be as likely driven by emergence as by 'governed' transformation. This implies both taking concrete steps to meet sustainable development goals, as well as strengthening coping and adaptation mechanisms.

Whether deliberate transformations at the scale, rate and extent that are called for are possible raises important research questions. The co-evolution of social, ecological and biophysical systems is deepening, suggesting ever more complex interactions, and as a consequence a widening potential for emergent features of change and hence greater uncertainty about futures. The degree to which these involve negative or positive feedbacks will determine whether they precipitate system innovation and reconfiguration, or system collapse. This raises two important research questions: Will the growing complexity and connectivity of social–ecological systems that we observe in the Anthropocene have a greater or lesser propensity for thresholds and tipping points leading to structural change? Does the growing complexity of these systems (and the attendant rise in the generation of emergent properties) make it more or less easy to promote and govern purposive transformations to sustainability?

In addition, seeking transformations to alternative futures will require fundamental reforms also in the way how societies are governed. Core questions of how to reform current political systems, from local through to global levels, become central in the debate on transitions towards more sustainable futures. Political systems need to be revised, for example, in ways that allow to adopt and change decisions more quickly. Institutional inertia, still a recurrent problem in local and global governance contexts, needs to be overcome by a careful redesign of existing institutions. Such political transformations, however, need to entail as well special attention to the accountability and democratic legitimacy of novel decision-making systems, preventing quick reflexes that could lead towards technocratic, top-down decision-making through state bureaucracies. Importantly, a transformation towards sustainability requires careful attention to the various drivers of unsustainability – including the role of the liberalized global economic system – as well as to existing relationships of power and persistent inequalities within and among countries. In sum, finding ways towards more effective, legitimate, and equitable earth system governance evolves into one of the core questions for the field of political science and law, requiring more research efforts (Biermann et al., 2012).

4. Examples of different scientific perspectives and purposeful approaches

Science is expected, more than ever, to provide critical knowledge to help guide humanity's path towards plausible, desirable and novel futures in the Anthropocene. The increasing complexity, non-linearity and uncertainty of Anthropocene means that science will be increasingly challenged to develop solutions to the problems societies face. The outcome of the proposed solutions is also hard to predict because – as we have seen – intentions often have unintended outcomes, and there are heterogeneities in, and mismatches between, the temporal, spatial and institutional distribution of the intentional actions and unintended outcomes (Bai et al., 2010a; Duraiappah et al., 2014).

Below we present three examples of concrete steps, one from each of the three groups of research questions presented above, that we think might respond to some extent to the challenges of the Anthropocene: (1) a different way of measuring societal progress; (2) a new modeling approach for looking into the future; and (3) a different science–practice relationship.

4.1. Towards a new way of measuring progress

Any purposeful approach to transition or transformation requires a framework to measure progress towards achieving the desired result. A key challenge in the Anthropocene is to ensure that humanity has the capability to achieve an overall state of well-being that is socially equitable and within regional and planetary boundaries (Raworth, 2012). How can we measure progress towards this goal?

Today's principal metric is the Gross Domestic Product (GDP) of nations. Politicians, policymakers and many economists today make two basic assumptions when designing policies to improve the well-being of citizens. The first assumption is that income is essential for improving well-being, and to increase income we need to ensure the continued growth of an economy's GDP—the total market value of the final goods and services produced in an economy. The second assumption is that the key asset required to maintain or increase GDP growth is the accumulation of what we call produced capital; these are the material goods such as buildings, factories and cars.

Both assumptions have been challenged and proven to be erroneous (Easterlin, 1995; Arrow et al., 2004; Kahneman et al., 2006; Stiglitz et al., 2010; Rogers et al., 2012). Defining well-being in a more relevant way can be a complex effort (Arrow et al., 2012), as while key elements in relational well-being are the same across contexts and cultures, cognitive well-being is context dependent and changing. An alternative is focusing on the productive base required to provide the constituents and determinants or the flows and ends of well-being. Recent economics literature identifies human and natural capitals as key inputs, which are also constituents of the productive base of economies (Dasgupta, 2001; Agarwala, 2012; UNU-IHDP and UNEP, 2014). Maintaining the productive base is essential if the well-being of societies is to be maintained and improved. Therefore, irrespective of what finally constitutes well-being, a tactical goal in sustainability analysis would involve ensuring that a society's productive base does not decline.

The need to track and monitor the productive base of an economy suggests the need to revise the way we measure progress. *We manage what we measure*. Some alternatives focus solely on tracking the constituents or ends of well-being, which include Bhutan's widely cited notion of Gross National Happiness Index, while others have an ad-hoc collection of both means and ends such as the Human Development Index. Both have problems. The former because it is so context dependent, the latter becayse of the methodological problems of attempting to add oranges and apples. An alternative is the Inclusive Wealth Index, which is an indicator based on a theory of sustainability (Dasgupta and Duraiappah, 2012).

The inclusive wealth of countries is the social value of the capital assets a country owns. Multiplying the stocks of the assets with the social or shadow price of the asset computes the social value of capital assets. In the case of some assets, these social prices can be represented by market prices while in other instances special efforts will have to be made to compute the actual value society places on these goods and services. At the moment only 18% of a country's assets are measured and monitored (UNU-IHDP and UNEP, 2014). The remaining 82% are either measured at the system periphery or treated as externalities of the system. The changes in the inclusive wealth of a country are equivalent to the changes in the well-being of the country at the aggregate level. As long as the changes in inclusive wealth are positive, changes in wellbeing are positive and this implies sustainability on the part of the countries. This index prompted a move away from focusing solely on the flow of income to an emphasis on monitoring the stock of assets that produce the flow of income as well as other goods and services critical for wellbeing. The index also prompts a move away from just focusing on income generation potential at the present moment in time towards focusing on the potential of assets to generate wellbeing for present as well as future generations.

The real change for the new era of the Anthropocene would require us to direct our attention away from flows and towards stocks, and for the present as well as the future. The Inclusive Wealth Index (IWI) does precisely this. A different way of measuring societal progress is important for Anthropocene futures, as while it originates from a different vision for the future, it also serves as a constant reminder of the societal goals and thus a mechanism to help achieving desirable futures.

4.2. Towards different approaches to scenarios

Scenario development plays important roles in exploring the future. Generally, thus far, scenarios have been positioned at the end of an argument that is built upon scientific understanding of extant conditions and drivers of the trends. But what if scenarios were taken as the *starting point* of the argument? Rather than present deviations from an existing trajectory, they could then inspire scientific research towards a better understanding of potential futures and their implications, including potential unintended consequences. In this sense, the use of scenarios can be extended to defining the range of futures that exist within and beyond the boundaries of safe and just operating space for humanity. Moreover, it might make it easier to identify scenarios that truly open up thinking.

What would that entail? Firstly, some recent advances in cognitive science might provide some clue, asking how the cognitive categories are formulated, and how decisions are made, both individually and collectively. Some of these have been discussed above. Among other things, this would open up the question of the relationship between feedback and feed-forward (anticipation), which is fundamental to human behavior (we all live between past and future), but which has thus far not been given its due in how we model or construct scenarios (Montanari et al., 2013; Sivapalan et al., 2014).

It would also imply exploring the role of creativity, intuition and imagination in how deal with uncertainty. Thus far, reductionist science has generally left these questions alone, or at least not studied them scientifically or integrated them in our scientific perspective on the world. Arthur (2009) broaches this issue at the interface of technology and economics, which can be extended beyond those domains, into the wider study of all our cultural and social institutions: what drives innovation in those domains? Are invention and innovation stochastic, as is often argued (Lane et al., 2009)? These remain open questions until a better understanding of the possibilities for facilitating innovations, and the spaces within which innovations occur.

Exploring multiple dimensions of innovation spaces are challenging but essential. One approach is to take a set of phenomena and projects them into a high-dimensional space to identify a large number of potential relationships between them (Fontana, 2012). The space is then reduced to fewer dimensions by determining which of these relationships cannot explain the phenomena at hand. Coupled with the enhancing capacity to collect and relate 'big data', this might be a fruitful path to reduce the path-dependency of scenario development. The computing power can be used not just to reduce complexity (as in the case of statistical methods), but to increase it.

A reconceptualization of the role of scenarios also includes a review of the field of economics, where discussion is often predominantly about the allocation of resources within existing (technological, social, institutional and environmental) structures. In light of achieving desirable future, more fundamental questions need to be asked: "How did the structure come about, and how might it change?", "What are the regulatory mechanisms involved?", "What happens when an existing structure becomes more and more complex?", "Does it become more efficient and/or resilient?", "What does that mean for its adaptability, its capacity to change?". A promising, emerging field of study is therefore the attempt to bring evolutionary thinking and complex systems approaches together with behavioral and other kinds of economics. A broader use of scenarios in public deliberations and collective decision-making would involve the option to explore the multiple relations with the situated knowledge of multiple stakeholders.

4.3. Towards a new relationship between science and practice

As discussed in Section 3.3, purposeful interventions are required to initiate and accelerate transition and transformation towards desirable future. Science has a crucial role to play in informing and designing such interventions, but to fully realize its potential, a new science–practice relationship is required.

The difficulties science encounters in handling futures, as discussed in Section 2, are further exacerbated when trying to inform decision-making, which is often based on understanding of past and present behaviors of the system. Under conditions of deep, second-order change, the structure and dynamics of a system is itself evolving. Knowledge production needs to better reflect the changing reality, and a rapid cycle that links knowledge and actions is required.

The traditional linear model of knowledge production and adoption where knowledge is produced by academia and then applied in society is insufficient and ineffective in addressing major societal challenges for the futures (Future Earth, 2013). Under this segregated model, even when knowledge and information is sufficient to take action, they are often not reflected in decisions and behaviors, and there are many examples where decisions are made against the best scientific knowledge.

In addition, the diversity of political and cultural contexts and structures around the world exacerbates this challenge because there is no single prescription for a better integration of science into decision-making. This demands a more dialogic relationship between science and society in responses to the collective dilemmas of the Anthropocene.

To deal effectively with this challenge, science itself needs to become more socially-robust (Gibbons et al., 1994). Solution-oriented research questions need to be asked, which are closely linked to major societal challenges (Lubchenco, 1998) and which can be pursued locally in the context of global sustainability. This requires closer linkages with societal stakeholders as one of the key failures lies in the lack of understanding of the psychology of society at different levels. Future Earth, a new 10-year international research program focusing on global change and sustainability, is spearheading efforts towards more integrative, interdisciplinary and trans-disciplinary research that effectively engages natural and social sciences and humanities. A key principle of Future Earth research is co-design and co-production, where scientists and, critically, societal stakeholders identify research questions and collaborate towards answers (Future Earth, 2013). National research foundations are increasingly developing strategic plans that focus on solutions-oriented science and collaborative research. One potential impediment to such a shift in focus is perhaps the cutting-edge culture of science and the institutional pressures within academia towards the new and novel within disciplines—when a focus on societal relevance is more in the realm of what Kammen and Dove called "mundane science" (Kammen and Dove, 1997). While disciplinary sectors may be resistant and defensive, the future of these disciplines is increasingly dependent on cooperating on larger challenges, bringing valuable specific expertise to contribute to broader questions, instead of solely focused on internal disciplinary dialogues.

It is important to recognize that for the questions that address fundamental challenges to society, neither natural nor social sciences are likely to be the sole provider of answers. Solutions might be distributed in the society and in practice. Much of the complex, non-linear and emergent behavior can only be understood within the diverse contexts and in the practices in which it occurs. Linking science to other knowledge systems might produce solutions-oriented synergies (Hoppers, 2002). Therefore it is essential to establish effective mutual learning and feedback mechanisms between science and practice; both science learning from practice and building knowledge to inform practice are needed here.

In terms of learning from practice, particular attention might be paid to the role of front-runners in innovative sustainable practices and experiments at different levels, and how to upscale them (Bai et al., 2010b; Berkhout et al., 2010; Leach et al., 2012). While these practices need to be subject to questions such as how to decide whether something is truly a good practice, good for whom, and for how long, it is important that we explore pathways to enable and upscale such individual efforts to bring about systemic change. To build up transferable knowledge, in-depth questions that are related to the mechanism of transition need to be explored, including what could trigger such an accelerated transition process, who can be the key actors, what are the enabling conditions, and what are the main barriers (Bai et al., 2010b). Such learning will then need to be put back and reexamined in the diverse context of real world practice. In the Anthropoce where different sectors and societies are increasingly connected, learning from practices and sharing them in other contexts has the potential to enable an expedited large scale transformation towards more desirable futures.

5. Conclusion

The Anthropocene has become an integrative concept able to accommodate various types of narratives and to incorporate human-environment interactions and impacts, including all sectors and thematic areas (Bonneuil, 2015; Brondizio et al., 2015). Much of the Anthropocene research agenda has focused on interpreting past and present instead of exploring the future, although the importance of doing so is beginning to be recognized (Berkhout, 2014). The proliferation of the concept of Anthropocene in society presents a unique opportunity to explore plausible and desirable futures, and the role of science in imagining, shaping and shifting towards such futures.

In this paper, we explored some of the scientific challenges associated with thinking about futures of the Anthropocene. These include epistemological and analytical challenges that need to be tackled jointly by scientists from multiple disciplines, yet our current scientific practices and institutional set up do not necessarily support such an integrative approach. In terms of deciding on the futures we want, it is essential to recognize the diversity of perceptions and understandings of the Anthropocene, and explore how we can adopt increasingly integrative and global perspectives, and yet firmly contextualize them in regional and local realities. In terms of understanding the major trends and underlying dynamics, we need to realize that the Anthropocene is changing the co-evolutionary pattern between humans and the environment- from an emphasis on local interaction to a coevolution of humanity and the planet as a whole. Such trends and patterns are the results of underlying drivers and societal dynamics, and require a shift away from deterministic single trajectory of future thinking towards exploring multiple trajectories and futures.

Understanding trends and impacts, underlying drivers and societal dynamics, and in particular the interactions, trade-offs and synergies across temporal and spatial scales, is required. In terms of transition and transformation towards desirable and novel futures, a better understanding of multi- and cross-scale interactions is critical in bringing about systemic, structural change. While recognizing that there are diverse and competing views of the potential for humanity to engage consciously with purposeful systemic change as well as preferences on the degree and direction of purposeful intervention, renewed attention to the science of social change is required.

In discussing futures literacy, Miller (2011) argues that “the challenge is not finding ways to know the future, but rather to find ways to live and act without knowing the future”. Yet, the futures of Anthropocene will the the outcome of today’s collective choices, and science has a strong role to play in guiding such choices. To fulfill this task, science needs to have closer and different relations with practice, where science is co-designed and co-produced with societal stakeholders, and where science not only informs practice but also learns from practice.

We argue that it is time for the sustainability debate to focus more on new opportunities offered by plausible and novel futures, including societies’ abilities to deal with risk and emergencies, rather than on how to share burdens to ensure the continuity of the present. The Anthropocene is the only -cene where the active agent within it is trying to define the -cene. The realization of the Anthropocene provides an opportunity not only to reconsider the power and consequences of human actions, but also how to channel the transformative and creative potentials of human society towards desirable and novel futures in the Anthropocene.

Acknowledgements

This article is part of a special issue titled “The Anthropocene”, which is a result of a collaborative effort involving the International Geosphere Biosphere Program (IGBP) and International Human Dimensions Program (IHDP). This paper and the special issue arose from a workshop supported by Grant #GEO-124560 from the US National Science Foundation to IGBP and funding from IHDP. We wish to thank all the participants of the workshop for the insightful discussions; the members of IGBP secretariat, in particular Sybil Seitzinger, Ninad Bondre, and Wendy Broadgate, for their support throughout the process; the three anonymous reviewers and the journal editors for their insightful comments on an earlier version of this paper; and Clive Hilliker for helping with the graphics.

References

Agarwala, M., 2012. Inclusive Wealth Report 2012: Measuring Progress Toward Sustainability. Cambridge University Press.
Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., 2014. IPCC Fifth Assessment Synthesis Report-Climate Change 2014 Synthesis Report.
Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Maler, K.-G., Schneider, S., Starrett, D., 2004. Are we consuming too much? J. Econ. Perspect. 147–172.
Arrow, K.J., Dasgupta, P., Goulder, L.H., Mumford, K.J., Oleson, K., 2012. Sustainability and the measurement of wealth. Environ. Dev. Econ. 17 (3), 317–353.
Arthur, W.B., 2009. The Nature of Technology: What It is and How It Evolves. Simon and Schuster.
Bai, X., McAllister, R.R., Beaty, R.M., Taylor, B., 2010a. Urban policy and governance in a global environment: complex systems, scale mismatches and public participation. Curr. Opin. Environ. Sustain. 2 (3), 129–135.
Bai, X., Roberts, B., Chen, J., 2010b. Urban sustainability experiments in Asia: patterns and pathways. Environ. Sci. Policy 13 (4), 312–325.

Bai, X., Chen, J., Shi, P., 2011. Landscape urbanization and economic growth in China: positive feedbacks and sustainability dilemmas. Environ. Sci. Technol. 46 (1), 132–139.
Bai, X., Shi, P., Liu, Y., 2014. Society: realizing China's urban dream. Nature 509 (7499), 158.
Barbier, E., Sathirathai, S., 2004. Shrimp Farming and Mangrove Loss in Thailand. Edward Elgar Publishing.
Beck, U., 1992. Risk Society: Towards a New Modernity. Sage.
Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., Martinez, L., McCowen, T., Murphy, K., Myers, N., 2009. Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. Proc. Natl. Acad. Sci. 106 (8), 2483–2489.
Berkhout, F., 2002. Technological regimes, path dependency and the environment. Glob. Environ. Change 12 (1), 1–4.
Berkhout, F., Verbong, G., Wieczorek, A.J., Raven, R., Lebel, L., Bai, X., 2010. Sustainability experiments in Asia: innovations shaping alternative development pathways? Environ. Sci. Policy 13 (4), 261–271.
Berkhout, F., 2014. Anthropocene futures. Anthropocene Rev. 1 (2), 154–159.
Berkhout, F., Smith, A., Stirling, A., 2004. Socio-technological regimes and transition contexts. System Innovation and the Transition to Sustainability: Theory, Evidence and Policy. Edward Elgar, Cheltenham, pp. 48–75.
Biermann, F., 2012. Planetary boundaries and earth system governance: exploring the links. Ecol. Econ. 81, 4–9.
Biermann, F., Abbott, K., Andresen, S., Backstrand, K., Bernstein, S., Betsill, M.M., Bulkeley, H., Cashore, B., Clapp, J., Folke, C., 2012. Navigating the Anthropocene: improving earth system governance. Science 335 (6074), 1306–1307.
Biermann, F., 2014. Earth System Governance: World Politics in the Anthropocene. MIT Press.
Biermann, F., Bai, X., Bondre, N., Broadgate, W., Chen, C.-T.A., Dube, P., Erisman, J.W., Glaser, M., Hel, S.v.d., Lemos, M.C., Seitzinger, S., Seto, K.C., 2016. Down to earth: contextualizing the Anthropocene. Glob. Environ. Change 39, 341–350.
Bonneuil, C., 2015. The Geological Turn: Narratives of the Anthropocene. In: Hamilton, C., Bonneuil, C., Gemenne, F. (Eds.), The Anthropocene Rethinking the Global Environmental Crisis. Routledge, pp. 208.
Bowles, S., Henrich, J., Boyd, R., Camerer, C., Fehr, E., Gintis, H., 2004. Foundations of Human Sociality: Economic Experiments and Ethnographic Evidence from Fifteen Small-scale Societies. Oxford University Press, Oxford.
Brondizio, Eduardo, O'Brien, Karen, Berkhout, Frans, Bai, Xumei, Carmen Lemos, Maria, Frank Biermann, Christophe Cudennec, Palma-Oliveira, Jose, Steffen, Will, Wolfe, Alexander, Chen, Arthur Chen-Tung. Re-conceptualizing the Anthropocene: a new call for collaboration. (submitted for publication).
Carpenter, S.R., Bennett, E.M., 2011. Reconsideration of the planetary boundary for phosphorus. Environ. Res. Lett. 6 (1), 14009.
Castree, N., Adams, W.M., Barry, J., Brockington, D., Buscher, B., Corbera, E., Demeritt, D., Duffy, R., Felt, U., Neves, K., 2014. Changing the intellectual climate. Nat. Clim. Change 4 (9), 763768.
Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. In: Chapin, F.I., Kofinas, G., Folke, C. (Eds.), Springer, Berlin.
Cole, D.H., 2015. Advantages of a polycentric approach to climate change policy. Nat. Clim. Change 5 (2), 114–118.
Costanza, R., Kubiszewski, I., 2014. Creating a Sustainable and Desirable Future: Insights from 45 Global Thought Leaders. World Scientific Publishing Co., Pte., Ltd..
Crutzen, P.J., 2002. The anthropocene. J. Phys. IV (Proc.) EDP Sci..
Dasgupta, P., 2001. Human Well-being and the Natural Environment. OUP Catalogue.
Dasgupta, P., Duraiappah, A., 2012. Well-being and wealth. Inclusive Wealth Report 2012. Measuring progress toward sustainability. U.-I. a. UNEP. Cambridge University Press, Cambridge.
de Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Curr. Opin. Environ. Sustain. 5 (3), 392–402.
Dearing, J.A., Yang, X., Dong, X., Zhang, E., Chen, X., Langdon, P.G., Zhang, K., Zhang, W., Dawson, T.P., 2012. Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. Proc. Natl. Acad. Sci. 109 (18), E1111–E1120.
Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., 2014. Safe and just operating spaces for regional social–ecological systems. Glob. Environ. Change 28, 227–238.
Douglas, M., Wildavsky, A., 1983. Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers. University of California Press.
Duraiappah, A.K., Asah, S.T., Brondizio, E.S., Kosoy, N., O'Farrell, P.J., Prieur-Richard, A.-H., Subramanian, S.M., Takeuchi, K., 2014. Managing the mismatches to provide ecosystem services for human well-being: a conceptual framework for understanding the New Commons. Curr. Opin. Environ. Sustain. 7, 94–100.
Easterlin, R.A., 1995. Will raising the incomes of all increase the happiness of all? J. Econ. Behav. Organ. 27 (1), 35–47.
Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B., 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. AMBIO: J. Hum. Environ. 31 (5), 437–440.
Fontana, W., 2012. Oral Presentation at a Workshop on Cancer. Arizona State University.
Fuller, T., Loogma, K., 2009. Constructing futures: a social constructionist perspective on foresight methodology. Futures 41 (2), 71–79.
Future Earth, 2013. Future Earth Initial Design.
Future Earth, 2014. Strategic Research Agenda 2014, Future Earth.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multilevel perspective and a case-study. Res. Policy 31 (8), 1257–1274.
Gell-Mann, M., 2010. Transformations of the twenty-first century: transitions to greater sustainability. In: Schellnhuber, H.J., Molina, M., Stern, N., Huber, V., Kadner, S. (Eds.), Global Sustainability—A Nobel Cause. Cambridge University Press, Cambridge, pp. 1–8.
Gerst, M.D., Raskin, P.D., Rockstrom, J., 2013. Contours of a resilient global future. Sustainability 6 (1), 123–135.
Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Sage.
Glaser, M., Glaeser, B., 2014. Towards a framework for cross-scale and multi-level analysis of coastal and marine social–ecological systems dynamics. Reg. Environ. Change 14 (6), 2039–2052.
Griggs, D., Stafford-Smith, M., Gaffney, O., Rockstrom, J., Ohman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., Noble, I., 2013. Policy: sustainable development goals for people and planet. Nature 495 (7441), 305–307.
Haberl, H., Fischer-Kowalski, M., Krausmann, F., Martinez-Alier, J., Winiwarter, V., 2011. A socio-metabolic transition towards sustainability? Challenges for another great transformation. Sustain. Dev. 19 (1), 1–14.
Hackman, H., St Clair, A.L., 2012. Transformative cornerstones of social science research for global change. Mundo Amazonico 4 (2013), 117–152.
Hamilton, C., 2013. Earthmasters: the dawn of the age of climate engineering. Yale University Press.
Hay, I., 2013. Geographies of the Super-rich. Edward Elgar Publishing.
Helbing, D., 2013. Globally networked risks and how to respond. Nature 51–59. http://www.nature.com/nature/journal/v497/n7447/full/nature12047.html.
Higgins, S., Overeem, I., Tanaka, A., Syvitski, J.P., 2013. Land subsidence at aquaculture facilities in the Yellow River delta, China. Geophys. Res. Lett. 40 (15), 3898–3902.
Holling, C.S., Gunderson, L.H., 2002. Resilience and Adaptive Cycles. Panarchy: Understanding Transformations in Human and Natural Systems, 25–62.
Hoppers, C.A.O., 2002. Indigenous Knowledge and the Integration of Knowledge Systems: Towards a Philosophy of Articulation. New Africa Books.
Hughes, T.P., Carpenter, S., Rockstrom, J., Scheffer, M., Walker, B., 2013. Multiscale regime shifts and planetary boundaries. Trends Ecol. Evol. 28 (7), 389–395.
Jaeger, C., Jansson, P., van der Leeuw, S., Resch, M., Tabara, J.D., 2013. GSS: towards a research program for global systems science. Berlin: Glob. Clim. Forum .
Janssen, M.A., Lee, A., Waring, T.M., 2014. Experimental platforms for behavioral experiments on social–ecological systems. Ecol. Soc. 19 (4), 20. doi:http://dx.doi.org/10.5751/es-06895-190420.
Kahnemann, D., Sloivic, P., Tversky, A., 1982. Judgment Under Unvertainty: Heuristics and Biases. Cambridge University Press, Cambridge.
Kahneman, D., Krueger, A.B., Schkade, D., Schwarz, N., Stone, A.A., 2006. Would you be happier if you were richer? A focusing illusion. Science 312 (5782), 1908–1910.
Kammen, D.M., Dove, M.R., 1997. The virtues of mundane science. Environ. Sci. Policy Sustain. Dev. 39 (6), 10–41.
Kasperson, R.E., Renn, O., Slovic, P., Brown, H.S., Emel, J., Goble, R., Kasperson, J.X., Ratick, S., 1998. The Social Amplification of Risk: A ConRenn, Ortwin. Risk governance: coping with uncertainty in a complex world. Earthscan, 2008. ceptual Framework. Risk Analysis 8, 177–187.
Kates, R.W., Parris, T.M., 2003. Long-term trends and a sustainability transition. Proc. Natl. Acad. Sci. 100 (14), 8062–8067.
Knight, F.H., 2012. Risk, Uncertainty and Profit. Courier Corporation.
Kroeze, C., Middelburg, J., Leemans, R., Escobar-Briones, E., Fennel, W., Glaser, M., Harashima, A., Liu, K.K., Meybeck, M., 2008. Integrating tools to assess changes in semi-enclosed marine systems. In: UrbanJr, E.R., Sundby, B., Malanotte-Rizzoli, P., Melillo, J.M. (Eds.), Watersheds, Bays, and Bounded Seas. The Science and Management of Semi-enclosed Marine Systems, Scientific Committee on Problems of the Environment (SCOPE) Series, vol. 70. Island Press, pp. 77–96.
Complexity Perspectives in Innovation and Social Change. In: Lane, D., van der Leeuw, S., Pumain, D., West, G. (Eds.), Springer Science & Business Media.
Leach, M., Rockstrom, J., Raskin, P., Scoones, I.C., Stirling, A.C., Smith, A., Thompson, J., Millstone, E., Ely, A., Arond, E., 2012. Transforming innovation for sustainability. Ecol. Soc. 17 (2), 11.
Lebel, L., Tri, N.H., Saengnoree, A., Pasong, S., Buatama, U., Thoa, L.K., 2002. Industrial transformation and shrimp aquaculture in Thailand and Vietnam: pathways to ecological, social, and economic sustainability? AMBIO: J. Hum. Environ. 31 (4), 311–323.
Lubchenco, J., 1998. Entering the century of the environment: a new social contract for science. Science 279 (5350), 491–497.
Meadows, D.H., 1999. Leverage Points: Places to Intervene in a System. Sustainability Institute, Hartland, VT.
Meadows, D., et al., 1972. The Limits to Growth: A Global Challenge. A Report for the Club of Rome Project on the Predicament of Mankind.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Current State and Trends. Island Press, Washington, D.C.
Miller, R., 2007. Futures literacy: a hybrid strategic scenario method. Futures 39 (4), 341–362.
Mitchell, M., 2009. Complexity: A Guided Tour. Oxford University Press.

Miller, R., 2011. Being without existing: the futures community at a turning point? A comment on Jay Ogilvy's "Facing the fold". Foresight 13 (4), 24–34.
Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Bloschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., Belyaev, V., 2013. Panta Rhei—Everything Flows: Change in hydrology and society—The IAHS Scientific Decade 2013–2022. Hydrol. Sci. J. 58 (6), 12561275.
Nisbett, R.E., 2003. The Geography of Thought. How Asians and Westerners Think Differently and Why. Free Press, New York.
O'Brien, K., 2012. Global environmental change II From adaptation to deliberate transformation. Prog. Hum. Geogr. 36 (5), 667–676.
O'Brien, K.L., Selboe, E. (Eds.), 2015. Social Transformation: the Real Adaptive Challenge. The Adaptive Challenge of Climate Change. Cambridge University Press, Cambridge.
O'Brien, K., Hayward, B., Berkes, F., 2009. Rethinking social contracts: building resilience in a changing climate. Ecol. Soc. 14 (2), 12.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.
Ostrom, E., 2010. Beyond markets and states: poly centric governance of complex economic systems. Am. Econ. Rev. 641–672.
Palumbi, S.R., 2001. Humans as the world's greatest evolutionary force. Science 293 (5536), 17861790.
Polyani, K., 1944. The Great Transformation. Rinehart, New York.
Raskin, P., Banuri, T., Gallopin, G., Gutman, P., Hammond, A., Kates, R., Swart, R., 2002. Great transition. Umbruche und Ubergange auf dem Weg zu einer planetarischen Gesellschaft. Materialien Soziale Okologie 20.
Raworth, K., 2012. A safe and just space for humanity: can we live within the doughnut. Oxfam Policy and Practice: Climate Change and Resilience 8.1. Oxfam, pp. 1–26.
Read, D., van der Leeuw, S., 2008. Biology is only part of the story. Philos. Trans. R. Soc. B: Biol. Sci. 363 (1499), 1959–1968.
Rees, W.E., 1995. Achieving sustainability: reform or transformation? J. Plan. Lit. 9 (4), 343–361.
Renn, O., 2008. Risk governance: coping with uncertainty in a complex world. Earthscan .
Renn, O., 2014. Towards a socio-ecological foundation for environmental risk research. In: Lockie, S., Sonnenfeld, D.A., Fisher, D.R. (Eds.), Routledge International Handbook of Social and Environmental Change. Routledge, London, pp. 207–220.
Rip, A., Kemp, R., 1998. Technological change. Human choice and climate change. In: Rayner, S., Malone, E.L. (Eds.), Resources and Technology, vol. 2. Batelle Press, Washington, D.C, pp. 327–399.
Rockström, J., Steffen, W., Noone, K., Persson, Å, Chapin III, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S.E., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475.
Rogers, D.S., Duraiappah, A.K., Antons, D.C., Munoz, P., Bai, X., Fragkias, M., Gutscher, H., 2012. A vision for human well-being: transition to social sustainability. Curr. Opin. Environ. Sustain. 4 (1), 61–73.
Rostow, W.W., 1990. The Stages of Economic Growth: A Non-communist Manifesto. Cambridge University Press.
Sen, A., 2011. The Idea of Justice. Harvard University Press.
Silva, C.L., Jenkins-Smith, H.C., 2007. The precautionary principle in context: U.S. and E.U. scientists' prescriptions for policy in the face of uncertainty. Soc. Sci. Q. 88, 640–664.
Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C.A., Wescoat, J., Rodriguez Iturbe, I., 2014. Socio-hydrology: use-inspired water sustainability science for the Anthropocene. Earth's Future 2 (4), 225–230.
Slaughter, R.A., 2002. Where now for futures studies? Futures 34 (3–4), 5.
Slovic, P., Finucane, M.L., Peters, E., Macgregor, D.G., 2004. Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk, and rationality. Risk Anal. 24, 311–322.
Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: are humans now overwhelming the great forces of nature. AMBIO: J. Hum. Environ. 36 (8), 614621.
Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015a. The trajectory of the Anthropocene: the great acceleration. Anthropocene Rev. 2053019614564785.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., 2015b. Planetary boundaries: guiding human development on a changing planet. Science 1259855.
Steward, J.H., 1955. Theory of Culture Change: The Methodology of Multilinear Evolution. University of Illinois Press.
Stiglitz, J.E., Sen, A., Fitoussi, J.-P., 2010. Report by the Commission on the Measurement of Economic Performance and Social Progress. Paris: Commission on the Measurement of Economic Performance and Social Progress.
Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, B., Midgley, B., 2013. IPCC, 2013. Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.
Sutton, M.A., et al., 2013. Our Nutrient World. Centre for Ecology and Hydrology.
Syvitski, J.P.M., Kettner, A., 2011. Sediment fluxes and the Anthropocene. Philos. Trans. R. Soc. A69, 957–975.
Tainter, J.A., Patzek, T.W., 2011. Drilling Down: The Gulf Oil Debacle and Our Energy Dilemma, Copernicus Publishers
Turner, G.M., 2008. A comparison of the limits to growth with 30 years of reality. Glob. Environ. Change 18 (3), 397–411.
Turner, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B., 1990. The earth as transformed by human action: global and regional changes in the biosphere over the past 300 years, CUP Archive.
Tversky, A., Kahnemann, D., 1974. Judgment under uncertainty: heuristics and biases. Science 185 (4157), 1124–1131.
Tversky, A., Kahnemann, D., 1981. The framing of decisions and the psychology of choice. Science 211 (4481), 453–458.
UN General Assembly, 2012. The future we want (Resolution 66/288) G. Assembly.
United Nations, 2013. Millenium Development Goals Report 2013.
UNU-IHDP and UNEP, 2014. Inclusive Wealth Report 2014: Measuring progress toward sustainability, Cambridge.
Urry, J., 2005. The complexity turn. Theory Cult. Soc. 22 (5), 1.
Van der Helm, R., 2009. The vision phenomenon: towards a theoretical underpinning of visions of the future and the process of envisioning. Futures 41 (2), 96–104.
van der Leeuw, S.E., Costanza, R., Aulenbach, S., Brewer, S., Burek, M., Cornell, S., Crumley, C., Dearing, J., Downy, C., Graumlich, L., Hegmon, M., Heckbert, S., Hibbard, K., Jackson, S.T., Kubiszewski, I., Sinclair, P., Sörlin, S., Steffen, W., 2011. Toward an integrated history to guide the future. Ecol. Soc. 16 (4), 2.
van der Leeuw, S.E., 2012. Global systems dynamics and policy. Complex. Econ. 1 (1), 3360.
van der Leeuw, S., Wiek, A., Harlow, J., Buizer, J., 2012. How much time do we have? Urgency and rhetoric in sustainability science. Sustain. Sci. 7 (1), 115–120.
Verburg, Peter H., et al., 2015. Methods and approaches to modelling the anthropocene. Glob. Environ. Change .
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277 (5325), 494–499.
Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.
Westley, F., Olsson, P., Folke, C., Homer-Dixon, Th., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banarjee, B., Galaz, V., van der Leeuw, S.E., 2011. Tipping towards sustainability: emerging pathways of transformation. AMBIO 40 (7), 762–780.
WHO, 2015. Health Through Safe Drinking Water and Basic Sanitation. Retrieved March 8, 2015, from http://www.who.int/watersanitationhealth/mdg1/en/.
Young, O.R., Berkhout, F., Gallopin, G.C., Janssen, M.A., Ostrom, E., van der Leeuw, S., 2006. The globalization of socio-ecological systems: an agenda for scientific research. Glob. Environ. Change 16 (3), 304–316.
Zalasiewicz, J., Williams, M., Waters, C.N., 2014. Can an Anthropocene series be defined and recognized? Geol. Soc. 395 (1), 39–53.
Zhang, Y., Shi, H.-L., 2013. From burden-sharing to opportunity-sharing: unlocking the climate negotiations. Clim. Policy doi:http://dx.doi.org/10.1080/14693062.2014.857979.
Zhang, K., Dearing, J.A., Dawson, T.P., Dong, X., Yang, X., Zhang, W.P., 2015. Poverty alleviation strategies in eastern China lead to critical ecological dynamics. Sci. Total Environ. 506–507, 164–181.