One Earth

Perspective

Transforming Sustainability Science to Generate Positive Social and Environmental Change Globally

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Despite the decades-long efforts of sustainability science and related policy and action programs, humanity has not gotten closer to global sustainability. With its focus on the natural sciences, sustainability science is not able to contribute sufficiently to the global transition to sustainability. This Perspective argues for transforming sustainability science into a transdisciplinary enterprise that can generate positive social and environmental change globally. In such transformation, the social sciences, humanities, and the arts can play an important role to address the complex problems of culture, institutions, and human behavior. To realize a truly integrated sustainability science, we need renewed research and public policies that reshape the research ecosystem of universities, funding agencies, science communications, policymaking, and decision making. Sustainability science must also engage with society and creatively employ all available sources of knowledge in favor of creating a sustainable Earth.

Introduction

Global environmental challenges are now manifesting at a planetary scale in the form of climate change, ocean acidification, biodiversity loss, environmental pollution, deforestation, and land-use change, among many others. These characteristics of the Anthropocene era have been driven by accelerating socio-economic trends, including population growth, various measures of consumption and economic growth, urbanization, telecommunications, and other aspects of globalization. The so-called Great Acceleration,[1] which started in the 1950s, has been compounded by the rapid development and spread of information technologies and telecommunications.[2]

Decades of international conferences and reports—beginning with the 1972 report *The Limits to Growth* by the Club of Rome and the United Nations (UN) Conference on the Human Development in that same year and evolving to the creation of the 17 Sustainable Development Goals (SDGs) by the UN General Assembly in 2015—have warned of the challenges and risks associated with current development pathways and have fostered the evolution of sustainability science at the global scale (Figure 1). Science has played a pivotal role in helping society to identify and understand the scope and scale of planetary environmental changes. It has also helped to guide policies and practices that address sustainability challenges from local to global scales. In recent years, global-scale challenges have become a growing concern. The 1990s saw the development of a number of global-change research programs and various environmental science initiatives, such as the World Climate Research Program, the International Geosphere Biosphere Program, Diversitas, the International Human Dimensions Program, and some attempted unification in the Earth Systems Science program.

Sustainability science emerged from the recognition of a need to extend global-change research to seek solutions, which in turn requires multidisciplinary and interdisciplinary research. This is slowly moving further from the perceived hegemony of the disciplinary expert toward the transdisciplinary co-design and co-production of research. International science coordination and funding approaches have also evolved over the past decades, as promoted by the International Science Council, the Belmont Forum, and others. Many of the global-change programs merged into Future Earth in 2013.[3,4] In 2018, a unified coordination of the natural and social sciences was advanced by the formation of the International Science Council through the merger of the International Science Union and the International Social Sciences Council. This year, the transdisciplinary Sustainability Research & Innovation Congress 2020 was planned to unite global researchers, industry practitioners, and world leaders to inspire action and promote sustainability transformation. Although the event is now postponed because of the coronavirus disease (COVID-19) pandemic, its aim of cultivating a space for sustainability scholarship, innovation, collaboration, and action won't be delayed. Global-change research reflects a growing demand for research to become more impactful and solution oriented, as spelled out in the Future Earth vision,[5] which is aimed at a multiscale (from local to planetary) understanding of environmental changes that transcend national boundaries. Over the past decade, global-change research has made significant efforts to be more inclusive of science communities from China, Russia, Africa, and the Global South.

Global-change research has first and foremost promoted a systems approach to environmental problems.[6] This approach has focused on relationships and interactions among the atmosphere, biosphere, hydrosphere, cryosphere, and soils and

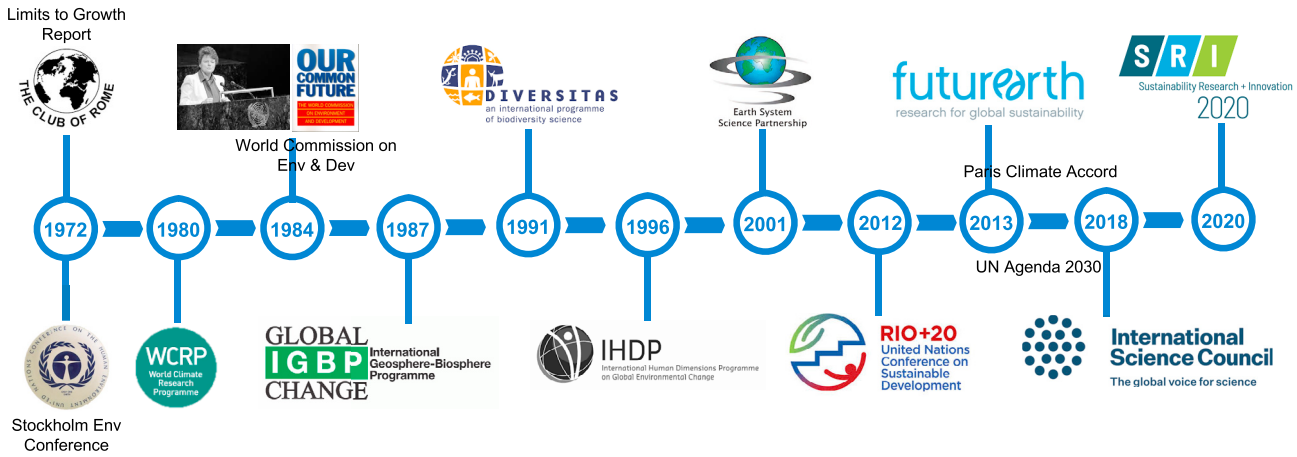

Figure 1. Significant Global Events in Sustainability Science

Global-change research evolved over the past half-century through interaction with major societal events, starting with the Stockholm Conference on the Environment and publication of *The Limits to Growth* by the Club of Rome. The report *Our Common Future* by the World Commission on Environment and Development popularized the sustainability concept. Research programs launched in the 1980s and 1990s supported the development of the Paris Agreement and SDGs in 2015, which further fostered the establishment of the International Science Council in 2018 and the world's first-ever transdisciplinary congress in sustainability in 2020.

explores how they are influenced by (and influence) human activities. An understanding of human impacts on Earth system processes gave rise to the notion of planetary boundaries,[1] the idea of tipping points,[7,8] and the concept of the Anthropocene. These scientific metaphors have been useful in articulating the risks of continuing with business as usual and development as usual.

It is fair to say that global sustainability science has contributed significantly to a number of global agreements to address the challenges of the Anthropocene, most notably the Paris Agreement and the UN Agenda 2030, which were signed in 2015. These universal agreements reflect a global consensus to address climate change and strive for sustainable and balanced social and economic development that promotes the well-being of socio-ecological systems. They also provide a powerful statement of intended direction for humanity, as captured in the UN's 17 SDGs. They create an imperative for transformative change in response to global challenges. However, such changes have not been forthcoming at the rate and scale required by global agreements. As a consequence, we continue to see increasing concentrations of CO_2 in the atmosphere, biodiversity loss, land degradation, and growing inequalities among people and nations.[9,10]

The Great Acceleration is generated and sustained by powerful economic mechanisms, including globalization, marketization, and financialization, which are based on the mainstream model of doing business and promoting economic growth.[11] To foster growth and maximize profit, companies and other organizations aggressively appropriate value as much as possible from nature and society and externalize the costs to natural ecosystems and to human communities, including future generations.[12,13] The mainstream business model drives competition and consumption and guarantees that human and social activities continue to drive the overuse of ecosystems beyond their carrying capacity toward breaching several planetary boundaries.[1] The current economic paradigm has led us to the point where the functioning of our global life-support system is no longer assured.[14] The global economy and functioning Earth system are on a collision course that will ultimately have dire consequences for humans and the biosphere; we need an urgent course correction, and current research paradigms are not meeting this challenge.

In this Perspective, we argue that in order to generate positive social and environmental changes globally, sustainability science must transform into a transdisciplinary enterprise. Our modest goal here is to lay out the special research challenges posed by the emerging Anthropocene era and exhort sustainability science to address these challenges impactfully. We focus our suggestions primarily on research policy measures that shape the conduct of science and agency of scientists and only secondarily on institutional policy measures. This is not intended to be a broad public-policy discussion on sustainability research. Sustainability science needs deep integration of the social sciences, humanities, and the arts with its dominant natural sciences. The focus should be on complex problems of nature, culture, institutions, and human behavior and the co-creation of knowledge with stakeholders. To do this, sustainability science and its stakeholders will need to better understand the funding dynamics and higher levels of research funding. To make sustainability science impactful, we need to modify the current research ecosystems. Sustainability science must engage with society (economic, social, and cultural spheres) to extend many successful small-scale seeds for change. The goal of sustainability science is to create a sustainable Earth by creatively deploying all available knowledge of humanity.

Anthropocene Challenges to the Research System

The evolution of what is now known as sustainability science has been important, but clearly it is not yet enough to play a pivotal role in social transformations needed for human preservation in the face of accelerating changes of the Anthropocene. We argue that we need to transform our approach to research itself. A number of known attributes of global change currently create

Table 1. Challenges to the Research System and Possible Responses

	Key Elements of the Challenge	Culture	Society	Behavior	Institutions
Rates of change	fast, non-linear environmental changes; slow social responses	–	new ways of learning	action research	–
Spatial connectivity	local solutions need upscaling to the global level	extended sensitivity for people living in distant places and cultures	–	–	supranational collaboration; global civil society organizations
Globalizing power dynamics	vested interests in market-based capitalism; widening gap between winners and losers	–	open public debates	–	stakeholder participation; fostering social innovations
Selective embeddedness of science in society	the influence of government and corporate funders; the problems of people in the informal economy are not addressed	more focus on human needs and ecological regeneration	the informal sector is outside societal regulations	–	supporting transdisciplinary projects and knowledge co-creation

challenges to research systems and their ability to analyze and contribute to global transformation.

Rates of Change

Not only are these changes fast, but in most instances they are also increasing non-linearly, as described by the Great Acceleration. The human capacity to respond to these changes has not kept pace. Some of the historical drivers of social change, such as generational turnover, have slowed as a result of increasing longevity. Consequently, cultural and value changes that influence how humans relate to the environment have to occur within a generation rather than over generations. Researchers themselves are challenged to think differently and engage in inter- and transdisciplinary research processes. However, it takes time to develop common understanding between disciplines and engage across different stakeholder knowledge epistemologies; therefore, integrative research risks lagging behind the changes it is addressing (Table 1).

Spatial Connectivity

Sustainability policies and practices must be local and context specific, yet they are embedded in larger systems that are increasingly and more rapidly connected. Although developments in inter- and transdisciplinary research over the past few decades have delivered much success at local levels in agriculture, development, and other domains, replicating this success across scales and globally is genuinely challenging. Transformations of social, economic, and institutional systems must also be negotiated across scales. Sustainability science research has not reconciled the gap between global-scale problems and locally based solutions. We still do not know how to scale up solutions in an interconnected world (Table 1).

Globalizing Power Dynamics

Social-ecological systems have always been affected by social and cultural norms, vested interests, and power dynamics. However, in today's globalized system, many social norms have been shaped by market-based capitalism and consumption, and the rates and distributed extent of change mean that managing the dynamics of winners and losers is increasingly challenging. For example, oil profits in one part of the world could finance investments that undermine sustainability interventions in another. At a time when there is a need to build engagement across all levels of society, identifying and transforming the nature of power relationships can be difficult. Sustainability science has not fully acknowledged or integrated global power dynamics into understandings of change (Table 1).

Selective Embeddedness of Science in Society

Science is extremely specialized and operates within universities and corporations, increasingly fulfilling the mandates of government and corporate funders. Science does not reach wide swathes of global society, particularly the communities where challenges of the Anthropocene are concentrated. Many sectors, especially the informal sector of the economy, are not benefiting from scientific knowledge. The informal sector accounts for up to 20% of global output in developed countries and over 33% in developing countries.[15] According to the International Labor Organization, two billion women and men make their living in the informal economy, which provides over 50% of non-agricultural employment in Africa, Latin America, and Asia.[16] In Africa, the informal economy could account for 50%–80% of the gross domestic product (GDP) and 90% of new jobs.[17] Even in sectors where science does influence economic and social decisions, it does not always effectively serve broad public interests. Science funding for the public good and commons protection is insufficient to address the massive and expanding problems of the Anthropocene (Table 1).

Above all, the challenges involve culture, society, behavior, and institutions. Yet, the current approach to sustainability science still pays insufficient attention to the social and human dimensions, and holistic integrated research remains the

exception rather than the norm. Sustainability science is still dominated by the natural sciences, and there is grossly less investment in the social sciences, the humanities, and arts than in the "hard sciences," as well as a general underinvestment in research overall. The uptake of research insights from the social sciences and the arts and humanities has been limited to the findings that fit within the existing paradigm.[18] Particularly debilitating is the failure to open up to new perspectives and different types of knowledge in the name of keeping science "objective" and apolitical.

Even where efforts have been made to integrate social, human, and natural sciences in transdisciplinary research, these successes are challenged by scale. In a recent review, Norström et al.[19] identified four key principles for good transdisciplinary co-production of knowledge: the engagement by research should be context based, pluralistic, goal oriented, and interactive. These principles, which draw on a great body of understanding from past transdisciplinary successes, are all challenged by the attributes of the Anthropocene. Engagement must be context specific, yet it seems to be required at all levels, including globally. It must be pluralistic, yet the diversity of stakeholders even at the local level is immense, and more so for global processes. Goal-oriented science is challenging with diverse actors across scales, and making engagement interactive, with feedback loops that promote reflection and learning, requires new thinking at the global level.

Systems thinking emphasizes that the most powerful leverage points for system change come through modifying the *design* and *intent* of the system.[20] Paradigms—or the shared thought patterns that influence the way that systems are perceived and designed—are also recognized as a powerful driver of systems change.[21] Understanding how to achieve paradigm shifts that influence the goals, values, and behaviors of systems is not the normal purview of the natural sciences. In fact, alternative paradigms are usually dismissed rather than encouraged within research systems. Although global assessment initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) recognize and include cultural beliefs, values, worldviews, and indigenous and local knowledge,[22] many perspectives from the social sciences and humanities have not been taken seriously in sustainability science. For example, research within feminist political ecology, decolonization studies, and "new materialism" offers new thinking on ethical and political challenges.[23,24] To capture the breadth and depth of global challenges, sustainability science needs to support efforts to recognize multiple perspectives and ways of knowing.[25] This includes developing profoundly holistic views on how natural and cultural systems coevolve.[26]

Interdisciplinary and transdisciplinary research activities in academic institutions are seeking such integration. There have been numerous attempts to encourage transdisciplinary collaboration and team science.[27] In higher-income countries, there is a tradition of collaborative cross-sectoral research, such as the agricultural extension research in the US and that conducted by the Cooperative Research Centres (CRCs) in Australia. Recently, the US National Science Foundation has encouraged research collaborations across science fields, which it calls "convergence science," by awarding grants for themes such as "navigating the new Arctic." Global programs such as Future Earth are developing "knowledge-action networks" to promote transdisciplinary research. However, the societal ecosystems in which such initiatives operate do not embrace their logic or provide resources to scale them globally as necessary. Current efforts to support integrated and transdisciplinary research do not match the scale of the problem.

Promoting Integrated Research

Maintaining the power of conventional, objective science has come at a cost for sustainability science. Not only has failure to integrate important insights from the social sciences and environmental humanities limited the perceived "solution space" for responding to global challenges, but sustainability science has also failed to engage with the "how" of transformative change. It has had limited success in connecting with key stakeholders (policymakers, corporate decision makers, political leaders, and civil society) through a language that they understand. It has also failed to convey not only the sense of urgency underscored by global changes but also the possibilities for responding. Currently, research on global environmental change largely speaks to the converted—to those who are influenced by rational arguments and scientific evidence. Very little attention has been paid to alternatives that challenge the tenets of conventional science and business as usual.

The normative dimension of sustainability science is one area that is often challenging to researchers. The question of which changes are ethical and the "right ones" to pursue introduces a normative dimension to science that can also be seen as highly political. However, this is an area where global agreements have provided direction for sustainability in recent years—the SDGs of Agenda 2030 clearly articulate normative visions for global sustainability in alignment with providing food, water, and energy to the approximately ten billion people expected to live on Earth by 2050, just as the Paris Agreement clearly states an intent to stay below 2°C warming, and 1.5°C if possible. Although they provide a strong statement of goals and intents, both still contain ambiguities around more detailed interpretations relating to different places, levels of governance, and interests, which together can limit their impact for sustainability.

To integrate the diversity of interpretations of particular goals, the research system has to open itself up to a wide range of disciplines and epistemologies. Many examples of existing research can contribute to a more integrative discourse within sustainability science. However, it is important to consider these different perspectives together rather than as separate boxes or silos. Drawing on an integral framework,[28] Figure 2 depicts how sustainability science has been largely confined to the domain of "systems" science and how less attention has been paid to behavior, culture, and experience. An integral approach to sustainability science includes a more balanced representation of these other three perspectives. Below, we highlight some specific examples of research in these other "quadrants" to illustrate the potential to broaden the systems-oriented perspective of sustainability science and deepen our understanding of how to respond to environmental change.

Behavioral Change

There is still a tendency within sustainability science to draw on the information-deficit model and assume that once individuals

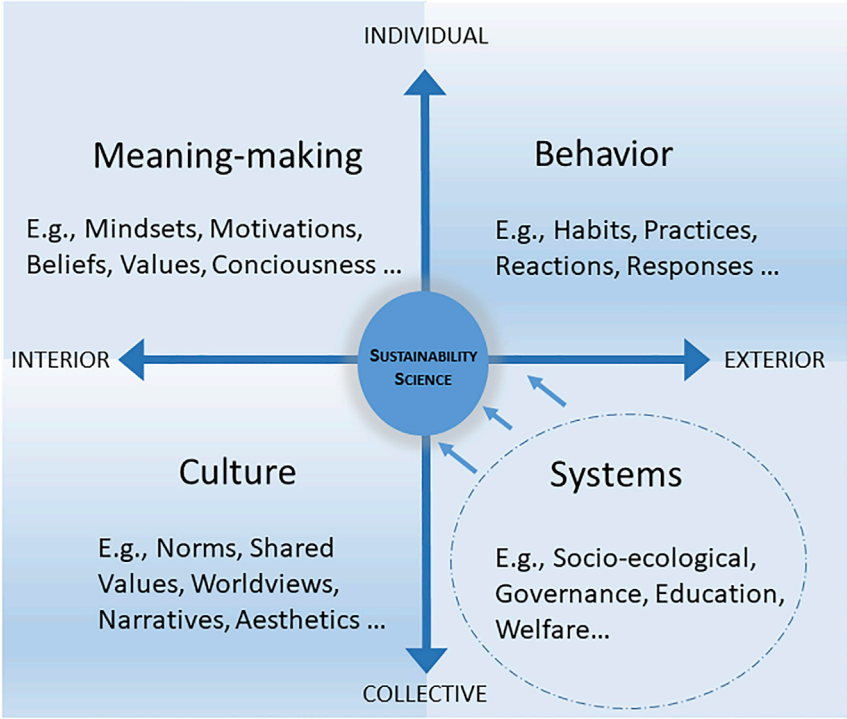

Figure 2. Toward Integral Sustainability Science

An integral framework recognizes four perspectives or domains of reality that present different types of knowledge about a subject, in this case sustainability science. Global-change research has tended to prioritize the systems domain and put less emphasis on research from the meaning-making, cultural, and behavioral domains. Integration does not diminish the systems perspective but rather adds valuable knowledge that can help society meet the SDGs. Adapted from Wilber.[28]

and organizations realize the risks associated with environmental change, they will take action or at least can be manipulated or nudged in that direction.[29] Yet, plenty of research in psychology—including research on the relationship between the intrinsic and extrinsic motivation of human actors, i.e., between motivation that is inherent in the task itself and motivation that relies on external rewards or sanctions[30]—shows that human behavior is more complex than this. The latter can result in the crowding-out effect, where external rewards actually reduce the intrinsic motivation of the actors. A crucial result of this mechanism is that people's environmental commitment declines and more environmentally harmful behavior emerges.[31,32] A key message here is that intrinsic motivation is critical to sustainable behavior within rapidly changing systems.

Research also describes how mechanisms of moral disengagement enable otherwise considerate people to commit transgressive acts without experiencing personal distress or guilt. In other words, moral control can be selectively disengaged from detrimental conduct through psycho-social mechanisms.[33] Selectively activated disengagement strategies (such as moral justification, euphemistic labeling, advantageous comparison, displacement of responsibility, diffusion of responsibility, disregard for or distortion of the consequences, dehumanization, and attribution of blame) are at work in harmful environmental practices of corporations and other economic entities.[34] This points to the need for a more critical engagement with the social structures and systems in which sustainability measures are enacted, as emphasized in social practice theory.[35]

Cultural Change

Embedding sustainability sciences and practices at a global scale will require a new and evolutionary narrative about human-environment relationships. Research on the power of narratives (language, metaphors, and storytelling) points to the need for new cultural narratives on the journey of humans in the universe across geological time.[36,37] The current narrative that humans are a special, privileged species destined to dominate over nature is deeply flawed, and it has contributed to a fascination with techno-fixes, such as geoengineering.[38]

Cultural changes need to embrace research on the power of the arts, aesthetic inquiry, and the humanities to heal the emotional disconnection between humans and nature, which is at the root of our current environmental crisis. The role of artists and art-based practices in achieving sustainability is increasingly being recognized.[39] Dutton[40] refers to the art instinct of humans as having survival value across cultures and time. Art is ubiquitous in all human communities globally over most of history. Communities able to tell better stories and draw better pictures of natural and predatory hazards were able to avoid annihilation more effectively. The rich human legacy of the arts also allows us to connect cognitive understanding to emotional empathy and embodied learning about sustainability.[41]

Changes in Experience

The experiential dimensions of environmental issues are becoming increasingly pronounced through emotions such as hope, grief, anger, and despair.[42] Whether and how we identify and respond to environmental problems are also closely tied to the ways that we perceive the world and our place in it. Issues such as climate change will be interpreted differently depending on the beliefs, values, and worldviews held by individual or groups.[43] Within psychology, meaning making is defined as "the process of how people construe, understand, or make sense of life events and experiences."[44] Research in developmental psychology shows that multiple worldviews coexist today and that these can change over generations and within individual lifetimes. Acknowledging both differences and developments in perspective-taking capacities and meaning making can provide insights into why people relate to sustainability issues differently and how to connect with a diversity of worldviews. For example, in a study of meaning making among farmers in El Salvador as it related to climate-change adaptation, Hochachka[44] found differences in the object of awareness, the

number of perspectives taken, the complexity of thought, and the scope of time considered in one's understanding of climate change and adaptation. Such findings suggest that it could be time for sustainability science to engage with the diversity and dynamics of meaning making rather than to assume that sense making of global challenges is universal and static.

In the three research areas described above, one can already see the ways in which researchers are synthesizing knowledge within and across the "quadrants" to study the dynamics of sustainability at a deeper level. For example, understanding behavioral changes involves grasping the processes of motivational crowding, understanding socio-cultural changes involves studying the narratives that underpin social values, and understanding experiential responses to environmental change involves in-depth research into meaning making. Yet, questions remain on how to forge this integrative research more broadly within sustainability science.

The integration of different perspectives and domains of knowledge and methodological approaches to research can be enhanced through awareness and education. Yet, disciplinary science has privileged cognitive modes of learning, and as disciplines have fragmented, so have the content domains of learning. In highly scientized fields such as medicine, expertise is being isolated and narrowed into increasingly restricted specializations. Education for global-change problems needs to be more holistic and contextually anchored through the incorporation of systems and their interconnectedness with culture and experience. Education that embraces an integrative discourse recognizes multiple perspectives and the need for critical thinking, reflection, and experience-based learning that leads to action and a sense of agency.[45]

One way of integrating different perspectives is through "action research," which focuses on driving change and doing rather than just reaching understanding.[46] Otto Scharmer and colleagues at the Presencing Institute created an action-research platform at the intersection of science, consciousness, and social change.[47] Their "Theory U" framework and methodology for leading profound innovation proposes that the quality of the results that people create is a function of the quality of awareness, or consciousness, from which the participants in the system operate. The inner shift, from fighting the old to sensing and presencing an emerging future, is at the core of deep leadership work.[48] People are encouraged to expand their thinking from the head to the heart. It is a shift from an ego-system awareness to an eco-system awareness that cares about the well-being of all, including oneself. The Presencing Institute has reached over 100,000 people in 185 countries to help leaders at any level find new solutions to the disruption that humanity faces.

There are a variety of approaches to linking research epistemologies with experiential knowledge systems. The CRCs in Australia have been a generally successful approach to making public funding contingent on a close working relationship between researchers and stakeholders, the latter of which provide funding input, in a vast array of different topics (https://www.business.gov.au/Grants-and-Programs/Cooperative-Research-Centres-CRC-Grants). CRC structures increasingly require a formal, even dominant, role for stakeholders in governance; even so, the growing experience suggests that it takes up to 5 years for the diverse partners to really work out a common mission and deliver on the promise of transdisciplinarity to get novel research into action. Another promising approach is through greater investment in coordinated, applied, local innovation hubs or sustainable development labs. At community colleges and universities in the US, "living labs" are using university operational facilities to create engaged action learning opportunities for students and engaged scholarship opportunities for researchers.[49]

Examples of integrated and holistic knowledge-creation and action initiatives that embrace more diverse epistemologies are also emerging from social and cultural institutions, as exemplified by the encyclical letter *Laudato si'* by Pope Francis.[50] The encyclical presents an integral ecology that underscores the human origins of the ecological crisis and proposes fundamental changes in organizing economic life. Among the important suggestions put forward by the Pope is increased frugality in consumption, and he also acknowledges the intrinsic value of nature. To realize his vision, Pope Francis initiated the Economy of Francesco project.[51] This international cooperative platform brings together 5,000 young economists, entrepreneurs, and change makers to co-create and put in place a new economic model in the spirit of integral human development.

Transforming Research

Notwithstanding the examples of integrative approaches described above, sustainability science has *not* been transformed enough to successfully address the mounting grand challenges faced by society. The challenge of evolving sustainability science cannot be just endogenous and isolated. Science is an instrument of society, and it operates within a broader socio-economic, cultural, and technological milieu that sets the operating context for research. At present, the external context is characterized by neoliberal capitalism that sets up competition rather than collaboration; devalues or overlooks social, human, and environmental capitals; fails to see systemic effects; and encourages inequality.[52] Science needs to rethink its social relevance and social connections to effectively contribute to the grand challenges of the Anthropocene. It must play an active role in the concurrent co-evolution of economies and their underlying cultural assumptions in sustainable directions. Within that broader context, scientific institutions and business organizations supporting science would need transformation of their core purpose, administrative processes, and reward systems. Sciences would need deep unification across epistemic and disciplinary lines and be willing to play a more active, participatory role in the transformations required for global sustainability in the world at large.

At a more synoptic level (see Figure 3), Waddell et al.[53] have argued that research needs to support the establishment of a "transformation system" in parallel with the system being transformed (see https://transformationsforum.net/). They outline four strategies that can contribute to transformation: doing change, forcing change, directing change, and co-creating change. According to these authors, most transformations involve a mix of all four types, and research can play a different role in each of these strategies. There is research to be done on actual transformations, as well as on transformation processes, practices, and pathways. Although systems thinking emphasizes that addressing design and intent are the strongest leverage points,[20] these

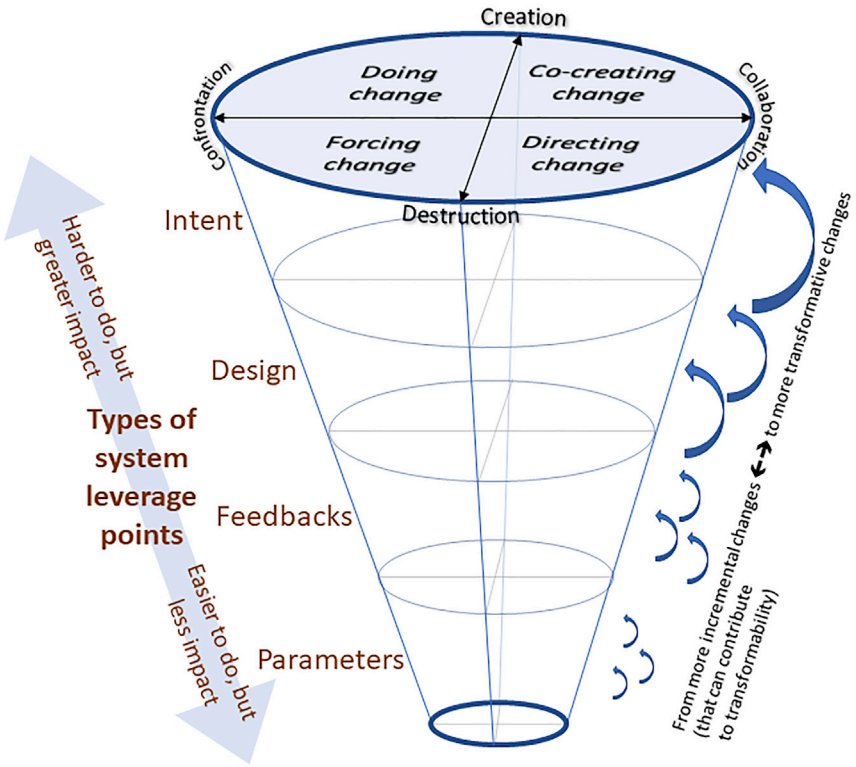

Figure 3. Pathways for Transformative Change

The cone of increasingly transformative change: systems interventions with increasing leverage (from bottom to top on left side[21,20]) as the cone opens out have greater potential to cause transformational change and require a larger application of the four strategies for systems change (top plane[55]); easier but directed incremental changes can contribute to the transformability of the system (right side).[56,57]

are also the hardest to achieve, particularly when the personal sphere of transformation is considered to be "external" or irrelevant to systems change.[43] An integration of experience, culture, behavior, and systems within sustainability science recognizes that the system is not "out there," and it highlights the importance of "being change," i.e., embodying the changes that are considered necessary at all levels, right here and now, and critical to the process of creating an equitable and sustainable future.[54]

Recognizing that people engage with the future differently is also essential for activating transformations to sustainability. The Three Horizons framework helps to generate agency and future consciousness by recognizing different ways of addressing uncertainty. This approach distinguishes between incremental and transformative change and emphasizes the need for participatory, reflective, and action-based research.[58] Research on how to pre-condition the system for transformation through incremental changes also provides valuable insights on how to create transformative change[56,57] by drawing, for example, on parts of the Australian wine industry that were adapting incrementally as opposed to transformationally.[57] When change is seen as a process, incremental changes offer an opportunity to shape the pathways for transformative change, as depicted on the righthand side of Figure 3, and thereby activate easier systems interventions (left side) in order to pre-condition the system for more transformative change in the harder systems characteristics of structure and intent. In practice, this requires a diversity of the intervention strategies (top of cone), as can be seen in examples such as the German energy transition or marriage equality in the US.[55] Then arises the question, how can similar insights be applied to sustainability science itself?

Enabling Sustainability Science Action

Sustainability science is a part of the global system that needs to transform to achieve the SDGs. This means that researchers have to reflect on how science should evolve from the research that is already available on transformations to research that can activate sustainability transformations in the wider world. We note four lessons in this regard, examine incremental changes in research organizations (where a great deal of science is operationalized), and then share some thoughts on how science can drive transformation across society.

First, most environmental problems, especially the global ones, are complex, messy, and wicked. Too often the problem formulation by researchers is partial and inadequate because they reduce the real-world, multifaceted problems into a single scientific-technical dimension and seek to solve this. Instead of providing a precise answer to the wrong question (i.e., committing an "error of the third kind"), approaches should address the full scope of the problem in question (the scientific-technical, the interpersonal-social, the systemic-ecological, and the existential-spiritual) and then develop some satisficing balance among them.[59] The job of sustainability science is to identify problems and then to produce response options that are substantively adequate and ethically acceptable in broad socio-economic contexts. The same logic can be applied to thinking reflexively about sustainability science itself.

Second, the growing literature on transitions and transformations in society covers the many dimensions and scales needed for responding to global environmental challenges.[60–62] Much of this research emphasizes small-scale (pilot) experiments as important to demonstrate proof of concepts. It also explores how local success stories can be scaled.[63] We need rapid cross-system learning about the successful ones in a context of changing the institutions and rules (scaling "up") and the cultural milieu (scaling "out") in which these can be scaled.[64] A growing set of examples and opportunities for scaling can influence how we do sustainability science.[65] We are at a point in time when sustainability science needs to think about how to selectively scale these exemplars massively, including the transformation of science itself.

Third, as already noted (Figure 3), systems thinking highlights how the strongest leverage points for changing a system are in

modifying its design and intent. It is usually much easier to fiddle with *parameters* and perhaps *feedbacks*.[20] The resilience literature addresses what makes a system more or less "transformable."[56] It highlights how important well-chosen incremental changes can be to pre-conditioning a system to be more likely to transform in the "right" direction when a suitable impetus comes along. Therefore, a good strategy for transforming sustainability science (as for transforming the world) should integrate well-directed incremental changes with preparedness to transform at the appropriate opportunity.

Fourth, enabling sustainability science to be impactful could also involve modifying the identity and role of scientists. Historically, the role of scientists has been to be "objective" observers of phenomenon, scientific data collectors, unbiased analysts, and accurate recorders and reporters of findings. In a world beset with grand challenges, scientists must also become translators of knowledge, communicators to the public, policymakers, implementors of action, advocates of solutions, and co-designers of the future. They must also listen deeply and maintain reflective, open minds as they engage not just with theory but also with actions that generate a sustainable world.

Preparing for Transformation

Noting these points, we turn to asking how sustainability science could become more pre-adapted to transform (bottom of Figure 3), as well as actually transform (top of Figure 3), in order to play a more effective participatory role in global transformations. This must be in the context of the challenges of the Anthropocene, i.e., that change is rapid, spatially interconnected, and more than ever influenced by global power dynamics as it is increasingly embedded into all societal systems. Acknowledging universities as a key operational venue of sustainability sciences, and knowing how difficult it is to change them, we suggest some modest yet potentially transformative incremental changes.

Progressing Incremental Changes in Research and Public Policy

Scientific research is guided by research policies and public policies, both of which progress through incremental changes. Research institutions, especially universities, are being challenged to produce impactful research. It is widely held that good transdisciplinarity (convergence science) is a means to greater and more enduring impact, especially in more complex and value-laden problems, such as many of the sustainability challenges discussed here. Such transdisciplinary challenges almost inevitably end up also requiring interdisciplinary approaches.[66,67] The incremental moves noted above from universities and funders toward promoting more inter- and transdisciplinarity must now be accelerated and empowered in both intent and design.

However, there are a number of well-recognized barriers to this—traditional mainstream pressures and incentives (e.g., university tenure based on citation counts and grant dollars or corporate instrumentality of research-delivering products); systemic problems in publication, granting, and training processes (e.g., difficulties in publishing integrated research, funding review processes that favor narrow disciplines, and under-resourced student training); and disciplinary research cultures of universities that undermine the commitment to inter- and transdisciplinarity and solving real-world public problems.[68] These barriers need to be systemically addressed. Change can be initiated if funders of science articulate more demand for impactful science. Funders should also modify the institutional constrains to addressing challenges in the Global South, where research funding is woefully inadequate and sustainability problems are also pervasive.

Universities where researchers are employed should modify tenure and promotion rules and reward systems to actively encourage transdisciplinary, solution-oriented sustainability science.[69] Even where inter- and transdisciplinarity are encouraged, we have noted that their co-design and co-production processes can be too slow to meet the rates of change we are experiencing. This could require additional resources to speed up these social processes. Many current funding mechanisms and processes do not recognize the need for these additional resources to be effective. However, we must also work harder to recognize where transdisciplinarity is really needed and where it is not. We must obtain better evidence for what works and what doesn't in multistakeholder processes so the resources can be transparently focused where they will have the best effect.

A critical impact of science-related public policies occurs via funding priorities. Inter- and transdisciplinarity need to be supported by a much greater investment in social science and the humanities if we are to promote an equal partnership across the disciplines. As noted earlier, this investment is miniscule in comparison with that in the natural sciences, even if these also are under-resourced. Even if we don't wait for more deep interdisciplinarity, many research areas require greater attention: understanding the deeply social nature of desire and consumption as it expands globally, mapping power dynamics across world consumer demand, exploring how culture change can support global transformations, rethinking the idea of "progress" in Western cultures, and understanding global social and cultural tipping points and other aspects of mobilizing leverage points for systems change.[8,70]

In addition to this improved investment, there should be a significant effort to improve holistic conceptual models and research practices that draw on multiple traditions. There is potential for increasing resources via government university and private-sector partnering.[71,72] These could help to resolve epistemological conflicts among the natural sciences, social sciences, humanities, and arts. This is important both interdisciplinarily (e.g., through conceptual models that deeply support the indivisibility and universality of sustainable development as framed by the SDGs) and also transdisciplinarily (e.g., through extended engagement and experimentation with traditional knowledge systems and faith-based systems).

Another key incremental and "no-regrets" step is increased training of researchers. This encompasses building the cohort of early-career researchers comfortable with interdisciplinary and transdisciplinary processes. We should also provide researchers with the skills to engage with stakeholders, convene and facilitate multistakeholder meetings, identify community problems that need to be addressed, and communicate results to the public and to policymakers. Effective co-evolution of science and society will also need to address joint training of the next generation of researchers and stakeholders so they will be able work together to meet sustainability challenges.

Last, we can begin to recognize reflexively that sustainability is itself an open-ended social learning process in which we all need to play a part. The notion of "being change" implies the need to "walk the talk." Sustainability scientists should be models of sustainable behavior yet also draw attention to the norms and systems that are impediments to sustainability. This means engaging in public debates and contributing to critical and reflective conversations about sustainability. Drawing on the experiences described in this paper, we should engage our own organizations to practice sustainability, drive toward net-zero carbon emissions and zero waste, and deliver gender equity and better social outcomes to meet the SDGs in our institutions and communities.[49]

Driving Global Transformations to Sustainability

Moving toward a transformational agenda for sustainability science implies not only driving the incremental change in the right direction but also being sufficiently active so that transformational interventions can take place rapidly when the opportunity arises.[73,74] For this we suggest a number of interlinked approaches.

First, building on the incremental efforts already taking place, sustainability science should be pursuing funding and other support for a large network of co-learning innovation hubs[75] in all sorts of contexts. These can be modeled in various ways (e.g., SDGs[10] and cities[76]). They share the attributes of obtaining close engagement between research and society at a local level in many projects in combination with a strong monitoring, learning, and knowledge-exchange infrastructure that enables success stories to be learned from and scaled rapidly in ways that are sensitive to understanding the contexts in which they will or will not work.[77] This transformation of the ivory-tower model of research not only provides an innovation scaffolding for transformation in society when the opportunity arises but also creates good outcomes at the local level in the meantime.[78,79] It also engages a much wider portion of society in discussions and learning about sustainability.

Second, sustainability science needs to engage in an action research mode with the high societal leverage points in such a way that an opportunity for transformation will lead these levers to be pulled in the "right" direction. Ethically, these should be in areas where the direction is both normatively justified by the framing of goals such as the SDGs and factually justified by research and analysis. Examples already noted include dramatic changes to our economic system away from narrow valuation of GDP to broader human well-being, the removal of structural barriers related to the skewed distribution of wealth and consequent inequalities, and a fundamental rejection of simplistic market-based capitalism, all of which are underpinned by a deep realignment of values to a more collaborative, reflexive, and kinder view of humanity's stewardship of our planetary home.[52] Needless to say, such changes would require supporting changes in all areas of institutional and governance design, but these are, of course, past human inventions themselves. The role of sustainability science (and scientists) here would be as activists, as envisaged in Waddell et al.'s "forcing change" quadrant.[53]

Third, in addition to playing this activist role, sustainability science needs to have a greater voice in societal processes, such as international UN governance discussions or discourse with global religions and traditional societies. The past attitude of scientists has tended to emphasize an autocratic expert identity. The transformed role must be as a partner among equals in seeking the normatively defined outcomes. Global-change research has sought this collaborative role, for example, at the UN Conference on Sustainable Development (Rio+20) and through the Intergovernmental Panel on Climate Change and IPBES assessment processes, but in the SDG development process it was still relegated to being one among many lobby groups. The UN Secretary General's Science Advisory Panel is still seen as a set of experts on the outside of the political process, as are most government scientific advisory boards. This is a failing on both sides of the relationship, and it must be worked on without hubris in policy and other domains.

Fourth and finally, sustainability science needs to be goal oriented to pursue transformation and accept the challenging roles implied by this. In the absence of clear intentionality in the design of these systems, science is dragged along by the dominant socio-economic forces that themselves should be the subject of change. Sustainability science should examine and prepare for its role in all the complementary transformation strategies noted by Waddell et al.[53]—understanding when to be an activist and when to partner and being ready to distribute these tasks in a credible way. The community of researchers and their co-design partners also need to accept the goal of transforming *themselves* to help enable *societal* transformation in order to meet the SDGs and thereby set the direction for all the above points. Maintaining transparency and accepting open debate while seeking sufficient consensus to move forward rapidly to achieve global sustainability and human well-being will be the hardest part of the balancing act.

Conclusions

It is difficult to reach final conclusions to the broad critique and transformational vision for sustainability science as explored in this paper. We acknowledge that the realization of this vision could take time, yet the current global situation is challenging assumptions about incremental and transformational change. Now is the opportunity for sustainability science to engage and co-evolve with the underlying socio-economic roots of environmental changes. Can the various branches of science afford to remain at epistemological odds with each other? Can research that is driven by funding needs and competition continue to serve private corporate interests rather than the public good? Research has not sufficiently emphasized how the most pressing environmental problems are caused and conditioned by social, cultural, economic, and business activities based on individualistic, competitive, profit-seeking models of economics and finance. If there has ever been a time to explore paradigm shifts that support an equitable and sustainable world, this is it.

In this article, we have offered some suggestions for moving sustainability science forward on its evolutionary path. Profoundly, on this path, the interlinked nature of science and society means that an overall societal commitment to sustainability (as articulated in the UN Agenda 2030) is a prerequisite for transforming science and society toward sustainability. For this to happen, macroeconomies would need to be designed for human and biosphere well-being rather than for financial economic growth.[80,81] Cultural values to support this economic transition

would be based on a more eco-centric vision of life and organizations.[82–87] Transformations like these require a different, more impactful version of sustainability science.

The research system of sustainability science itself needs to evolve rather than just seek to change everything else. This means that sustainability scientists and policymakers have to be more reflexive and challenge their own limiting assumptions related to global change. Global sustainability research and practices strive to provide adequate food, water, energy, income, education, resilience, voice, jobs, health, and gender and social equity for all in an ecologically safe operating space for humanity.[88] This will require weaving together models of economic growth with models of ecosystem changes and managing winners and losers and the related changes in power dynamics. It will also require addressing the structural economic barriers that have emerged over the past century. The most important of these is wealth and income inequality.[89] Currently, 50% of wealth is owned by less than 1% of the world population. Two billion people still consume under $2 per day and aspire to increase it. Growing inequality makes ''economic growth'' ineffective at addressing the needs of vulnerable sections of society by concentrating wealth with the rich. The co-evolution of sustainability science and sustainable societies implies increasing consumption of some and decreasing consumption of others without degrading ecosystems.

The research ecosystem of universities, funding agencies, policymakers, and decision makers needs to be modified in other ways. Science operations are different in each country, and there is no one-size-fits-all solution. Some general actions for consideration include the following:

- Universities explicitly prioritize impactful research on environmental grand challenges.
- Universities adjust their research productivity, measurement methods, and reward systems to beyond academic measures (publications, citations, and grant dollars) to include the impact on social and sustainable development metrics.
- Funding agencies make more stringent and concrete demands that research should have an impact on sustainability (via the SDGs) in communities.
- Science communication with policymakers and with the public should be made a priority.

Many global environmental changes are being addressed outside academia through citizen activism, non-governmental organizations, and social movements. Sustainability science could be leading some of these activities instead of merely studying or observing them. However, in order to take such leadership, researchers will need to acknowledge that science is not just a neutral objective pursuit of knowledge when it comes to sustainability. By bringing in reflexivity, values, and ethics, they can justify participation in structural and systemic changes that would produce an equitable and thriving world. Scientific pursuit of knowledge involves much more than constructing accurate and analytically powerful representations of the world. Knowledge should inspire people to both reflect and act. To change society for the better, we need to creatively activate and employ all available sources of human knowledge in favor of creating an equitable and sustainable Earth.

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