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Reflections on the past and future of whole Earth system science

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Abstract

Non-technical Summary. With unabating climate extremes, evidence of waning biosphere buffering capacity, and surging ocean surface temperature, Earth system analysts are posing the question: is global environmental change accelerating, driven by the depletion of our planet's resilience? No scientist contributed more actively to addressing this question and thus defining sustainable development in the Anthropocene than the late Professor Will Steffen. His contributions to Earth system and global sustainability research gave birth to concepts such as the Planetary Boundaries, Hothouse Earth, Planetary Commons, and World-Earth resilience, and have become guideposts for how Earth system science can inform humanity's Earth stewardship in the Anthropocene.

Technical Summary. Mounting evidence of accelerating global environmental change is driving scientists to question whether we are witnessing a breakdown in the resilience of our planet. Three lines of scientific enquiry have been important when studying the stability and resilience of the planet: the empirical evidence of the great acceleration of the human enterprise from the 1950s onwards resulting in planetary-scale pressures; the understanding that Earth is a complex biosphere-geosphere system with self-regulating interactions and feedbacks contributing to control its equilibrium state; and the emerging insight into the unique stability of the Holocene Epoch, the last 10,000 years of inter-glacial equilibrium, and its critical role in providing predictable (and for humanity agreeable) life conditions for the evolution of modern civilizations. Professor Will Steffen played a pivotal role in integrating and advancing these three Earth system research avenues and combining them into one integrated people-planet framework Earth system. State-of-the-art research on fully coupled Earth system models (ESMs) that also integrate non-linear dynamics and tipping-point behavior, and even human dynamics, is built in part on Will Steffen's pioneering work to observe and describe the Earth in the Anthropocene.

Social media summary. Prof. Will Steffen's legacy and how Earth system science can inform humanity's Earth stewardship in the Anthropocene

1. Introduction

The year 2023 registered the hottest northern-hemisphere summer on record, manifesting in devastating heatwaves in China, Southeast Asia, Europe, and the US. Sea surface temperatures also broke records in the Mediterranean Sea and off the coast of Florida, symptomatic of sky-rocketing ocean-heat content. Floods and hurricanes buffeted the US, China, and Brazil, while the Mediterranean storm 'Daniel' caused the deadliest weather event of 2023 in Libya. Wildfires in Greece, Canada, and Hawaii were both destructive and responsible for severe degradation of air quality. The climate realities of this and recent years pose a fundamental question to those studying the Earth system: are we seeing an acceleration of global environmental change, caused by a breakdown in the resilience of our planet? (Ripple et al., 2023)

In responding to this question over the past 30 years, scientists have been able to draw on three lines of scientific inquiry providing deep new insights into global sustainability (Rockström et al., 2009a, 2009b), which have fundamentally shifted the academic landscape and given birth to a new perspective on our Earth as a whole. The first is the empirical evidence of the great acceleration of the human enterprise (Steffen et al., 2015b), laying the foundation for declaring a new geological epoch, the Anthropocene (Zalasiewicz et al., 2019). The second is the scientific advancements, in line with the Gaia theory (Lovelock, 1979), providing evidence that the Earth system is an integrated and coupled (across the entire biosphere-geosphere), complex and adaptive system, regulated by biogeochemical and physical feedbacks and interactions. This provides the scientific context for more recent progress in identifying non-linear dynamics and cascades in the Earth system, shifting attention to resilience theory (Folke et al., 2010), Earth resilience and tipping points (Lenton et al., 2008), resulting in a shift in mindset from certainty and incrementality, to uncertainty, irreversibility, and abruptness. The third is the emerging insight into the unique stability of the Holocene epoch, and its critical role in providing predictable (and for humans agreeable) environmental conditions for the evolution of modern civilizations (Feynman & Ruzmaikin, 2007). Evidence of its exceptionality adds to the significance of the Holocene being the only state of the Earth system we know for certain can support the modern world as we know it (Rockström et al., 2009a, 2009b).

No scientist in the world was more actively involved in advancing these three Earth system research avenues and combining them into one integrated people-planet framework – thus defining sustainable development in the Anthropocene – than the late Professor Will Steffen. His life contributions to the frontier of Earth system research and global sustainability gave birth to defining concepts such as the Planetary Boundaries, Hothouse Earth, Planetary Commons, and World-Earth resilience, and have become guideposts for how Earth system science can inform humanity's task of becoming Earth stewards in the Anthropocene.

2. Anthropocene and the great acceleration

In the year 2000, Paul Crutzen, Nobel Laureate and then vice-chair of the International Geosphere-Biosphere Programme (IGBP), proposed at a meeting of the IGBP (then headed by Will Steffen) that Earth had left the Holocene as a result of rapidly rising human impacts on the Earth system and entered a new geological Epoch, the Anthropocene (Crutzen, 2002; Crutzen & Stoermer, 2000). Speculations on the starting date began immediately (and continue to this day), with Paul Crutzen suggesting the start date of the Anthropocene be placed near the end of the 18th Century, that is, at the start of the industrial revolution. Will Steffen and the IGBP decided to put this question to the test, resulting in the 'Great Acceleration project', which produced the now classic graphs of 'hockey stick' patterns of accelerated human pressures on the Earth system from the 1950s onwards. This was first published in a major Earth system synthesis book by the IGBP (Steffen et al., 2005). Twelve indicators of socio-economic drivers of the human enterprise and 12 features of global change of the Earth system were mapped. This provided the scientific foundation for the evidence that the world has shifted from a relatively small world on a big planet, to reaching a saturation point of a relatively large world on a small planet in just 50 years. The 'Great Acceleration' data was updated in 2015, leading to the conclusion by Will Steffen and his co-authors that the most convincing start date of the Anthropocene, from an Earth system perspective, is at the 'hockey stick' pivot moment in the mid-1950s for essentially all environmental change processes. It is only now that there is clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of variability of the Holocene and driven by human activities (Steffen et al., 2015a).

This scientific legwork by Will and colleagues across the Earth system science community, led to the establishment in 2016 of the Anthropocene Working Group (AWG) of the Sub-commission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS), tasked with assessing whether there is enough scientific evidence to justify declaring a new geological epoch. In 2017 the group laid out clear scientific evidence for an Earth trajectory away from the Meghalayan Stage of the Holocene epoch, into the Anthropocene epoch (Zalasiewicz et al., 2017). In the SQS vote in 2019, a clear majority voted in favor of redefining the current Geological time scale, from the Holocene to the Anthropocene, with the most likely onset being in the mid-20th century, in line with the Steffen et al., work on the Great Acceleration (http://quaternary.stratigraphy.org/working-groups/anthropocene/) (Zalasiewicz et al., 2019).

This scientific journey, from the proof that humanity faces not one (carbon) but multiple hockey-sticks of exponentially rising human pressures on the life-support systems on Earth, to establishing the Anthropocene as a new geological time unit is, in my view, the most important scientific insight and message to humanity in modern times. It is not only a fundamental shift in our relationship to planet Earth, it changes everything. In the Anthropocene, where the world (the sum of human activities) is threatening the stability of Earth, humanity must become stewards of the entire world-Earth system (Folke et al., 2021).

3. Tipping points/earth resilience

More or less simultaneously with the scientific advancements of the empirical observations underlying the Great Acceleration and the Anthropocene, more and more science was showing that the response in the Earth system to the 'Anthropocene pressures' could be abrupt, irreversible and amplify change. The seminal climate tipping elements paper was published in 2008 (Lenton et al., 2008), and the evidence of catastrophic regime shifts in ecosystems was published in 2003 (Scheffer & Carpenter, 2003), supported by the regime shifts database work of the Resilience Alliance (https://www.resalliance.org/thresholds-db). Will Steffen connected these strands of research – on the Anthropocene, climate tipping elements, and biosphere regime shifts – into a broader synthesis of a planet under pressure (Steffen et al., 2011).

This work opened up a whole new avenue of scientific inquiry into Earth resilience, focused on understanding the capacity of complex and inter-connected biophysical systems on Earth to dampen and buffer stress and shocks through negative feedbacks. Will Steffen's contributions to and support of the Global Carbon Project (Friedlingstein et al., 2023), which maps the global carbon uptake in oceans and land-based ecosystems and monitors and analyses ocean heat and carbon uptake through both physical and biological processes, are key in this respect.

These advancements in Earth system science also led Will Steffen to advance, in my mind, the most fundamental of all research questions facing humanity: now that we are in the Anthropocene, is the Anthropocene trajectory at risk of compounding into a new state? Will Steffen believed the Anthropocene to be both a pressure *and* a trajectory. The modern world is now the dominating force of change on Earth, exceeding the (still prevailing) natural forces of solar orbiting, El Nino oscillations, volcanic eruptions, and Earthquakes. The Earth system is being pushed along a new trajectory and we are gradually 'gliding away' from the stable inter-glacial Holocene conditions we have been privileged to inhabit over the past 12,000 years. However, as far as we know today, the Anthropocene is not yet a new *state* of the planet. We have not tipped the entire Earth system into a new logic of feedbacks dominated by self-amplified warming and thereby fundamental shifts in hydrology, ice dynamics, biochemical cycles, net primary production (NPP), and genetic diversity. The 'big' question then, postulated in one of Will Steffen's most cited papers (Steffen et al., 2018) is this: if human caused climate forcing reaches 2 °C, what are the risks that the Earth system will transition from carbon and heat uptake to release, and thereby catalyze an irreversible drift away from the inter-glacial Holocene state towards a new 'hot' state.

4. Hothouse earth

This hot state was coined 'Hothouse Earth' (Steffen et al., 2018). Synthesis of published research led to the conclusion that 2 °C anthropogenic forcing can lead to an additional 0.4 °C additional warming, due to shifts in biosphere feedbacks (forest dieback, permafrost thawing, albedo shifts, and gradual decline in soil and ocean carbon uptake). The hypothesis was (and still is) that this may kick-start a cascade of regime shifts and triggering of tipping elements (Martin et al., 2021), which could lead to further warming. If this exceeds the negative feedbacks, particularly from carbon and heat uptake in the ocean, we risk an unstoppable drift. The Anthropocene shifts from trajectory to state.

This is not only a scientific frontier for Earth system research. It is also a global call to action, as it provides strong evidence of urgent and catastrophic risks. Will Steffen was deeply engaged in the cross-section between climate science and policy, e.g. as one of the lead scientists of the Australian Climate Council, and he was a co-author of the recently published 'Climate Endgame' paper, which highlights risks of moving beyond manageable global environmental change and the need for immediate and transformative action (Kemp et al., 2022).

5. Holocene stability

The evidence of Holocene stability has been reinforced over the recent years. Up until 2021, we could argue strongly in support of the unique stability of the Holocene, with ice-core data indicating a global mean surface temperature (GMST) varying by 1 °C above and below the pre-industrial 14 °C average (Schellnhuber et al., 2016). In 2021 the most recent authoritative synthesis of Holocene temperature variability was published by Osman et al. (2021), refuting our conclusion. The Holocene was even more stable than we had argued, with GMST varying by only 0.5 °C around the 14 °C mean. One of Will Steffen's most recent, and still unpublished research projects explores whether this environmental stability (for climate) is also evident in other planetary boundaries, like global hydrology, forest cover, net primary production (NPP), and biome composition. While this work is still ongoing, it shows that porous data and regional variability make biosphere parameters much more difficult to assess compared to global temperature. Also, it seems clear that it was not until the Meghalayan Stage, starting around 6000 years ago, that the Earth system finally reached a 'Holocene equilibrium', as a result of the slow transitions, particularly related to ice melt and sea level rise (after leaving the last Ice Age some 20,000 years ago). However, the findings so far indicate that both NPP, a key indicator of biological energy flows, global hydrology, and biome composition, evolved within a narrow range, when aggregated to an Earth-system scale, throughout the Holocene. This further supports the theory that environmental stability on Earth – in terms of temperature, rainy seasons, and thus growing seasons – was critical for the domestication of animals and plants and thus for the first agricultural revolution.

This is significant. We have been present on Earth as modern humans for at least 200,000 years (existing through two glacial/inter-glacial cycles) (Galway-Witham & Stringer, 2018), and it is not until we entered the Holocene that we transitioned from hunter-gatherers to sedentary, rural communities. Recent debates on the archeological interpretation of human history on Earth suggest a dramatic re-writing of human origins. Graeber and Wengrow (2021) argue that there is ample archeological evidence of advanced societal structures and infrastructure development well before the Neolithic Revolution, i.e. during the last Ice Age. This contradicts conventional thinking that humans lived in small, confined 'savage' hunting communities prior to the Holocene, and only in the Holocene transitioned to the large, 'empire-building' societies of the Inca, Maya, Mesopotamian, Pharaonic Egyptian, and (Chinese) Xia dynasty. If they are right that modern humans were able to construct monuments and execute large-scale 'Göbekli Tepe' institutions even in Ice Age conditions, where does that leave the argument that the Holocene is the only state that can support the modern world as we know it? My conclusion, though admittedly speculative, is that it strengthens it even further. If we already had the capacity to develop advanced institutions and build grand monuments in the harshest cold of the last Ice Age, then nothing should have hindered us from inventing agriculture and becoming farmers, and thus sedentary dwellers in ever larger and increasingly complex societies. But we did not do it. Why not? Clearly not because of a lack of social and intellectual skills. My hypothesis is that we simply lived on a planet where the risks associated with the investment in planting seeds and herding cattle were too high. Not until spring, summer, autumn, and winter (long enough growing seasons from the perspective of rain and temperature) returned predictably, year after year, did we dare to transition from foragers to farmers.

6. Planetary boundaries

The integrated synthesis of all these strands of Earth system science – the great acceleration, the Anthropocene, Earth resilience and tipping points, and the Holocene as Earth's benchmark for a livable planet – resulted in the Planetary Boundary framework (Rockström et al., 2009a, 2009b). A cornerstone of the Planetary Boundaries framework is the unique role of environmental stability on Earth during the Holocene for the emergence of sedentary farming communities as a result of the Neolithic revolution in the early phase of the Holocene some 10,000–12,000 years ago, and the subsequent emergence of modern civilizations as we know them (Rockström et al., 2009a; 2009b; Rockström & Gaffney, 2022). In fact, evidence of our profound dependence on environmental stability in the Holocene makes it possible to quantify 'safe boundaries' for all biophysical systems and processes on Earth that contribute to regulating the state of the Earth system. The 'safe' levels are set to provide humanity with a high likelihood of keeping Earth in a 'Holocene-like state'.

Will Steffen led the first scientific update of the Planetary Boundaries framework (Steffen et al., 2015b), which introduced the notion of 'core boundaries' (which include climate, biosphere integrity, and novel entities). The core boundaries derive from the evidence that, on their own, they are capable of destabilizing the Earth system and their fates are closely interlinked with process interactions with other boundaries, for example, the role of freshwater in securing carbon sinks and ecosystem functions.

Will Steffen was a strong advocate of the 'biosphere boundaries', that is, the four planetary boundaries (biosphere integrity, freshwater use, land system change, and biogeochemical flows) which are fundamental in regulating resilience in the Earth system, while not necessarily exhibiting evidence of planetary-scale tipping points. A key scientific challenge has been to find adequate control variables (in order to quantify safe boundary

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levels) for the Biosphere integrity dimension of functional diversity (in 2009 extinction rate was proposed as the control variable for genetic diversity, and has stayed as such since then). Originally, we proposed Mean Species Abundance (MSA) as a proxy indicator for functional diversity. In 2015 we changed this to the Biosphere Intactness Index (BII). Both MSA and BII have limitations, ranging from global data gaps to unclear links between ecosystem functioning and the control variable. For the 2023 scientific update, we have substituted BII with Net Primary Production (NPP), setting the safe boundary at a maximum of 10% Human Appropriation of NPP (HANPP) (with an uncertainty range of 10–20%) (Richardson et al., 2023). This follows evidence provided by Steve Runnings already in 2012 (Running, 2012), who proposed NPP as a 10th potential Planetary Boundary, and a strong conviction by Will Steffen, that NPP is a good proxy for biome-scale functional diversity from an Earth system perspective.

7. Future directions of Earth system science

In a recent synthesis, Will Steffen concluded that Earth system science (ESS) is increasingly integrating human and environmental, world and Earth dimensions, and is a rapidly emerging transdisciplinary endeavor (Steffen et al., 2020). The evidence emerging from multiple strands of disciplinary science, coupled with Earth observations of rising frequency and severity of extreme events (Seneviratne et al., 2021), places Earth system science at the frontier of addressing the following scientific question: are we at risk of destabilizing the entire Earth system (and thus drifting irreversibly away from a state that can support our modern world)? Or phrased in another way: how stable and resilient is the Earth system? Is there a risk that tipping point and cascade dynamics can generate a planetary tipping point, or is Earth's inherent biogeophysical buffering capacity strong enough to stave off an irreversible drift away from inter-glacial Holocene-like conditions on Earth? (Rockström et al., 2021).

These key science questions go beyond the current state of the art, requiring a fundamental advancement of Earth system models (ESMs), not only coupling cryosphere, hydrosphere, biosphere, and atmosphere processes but also integrating non-linear dynamics and tipping-point behavior (irreversible shifts in feedbacks) in both climate and biosphere. The recent initiative to develop a Tipping Point Model Intercomparison Project (TIPMIP), and other research consortia looking at tipping points (e.g. TipESM and CLIMTIP) across the climate modeling community is an example of how ESS is increasingly assessing and integrating interactions, feedbacks and non-linear dynamics in the Earth system.

Nonetheless, critical transitions in the Earth system remain uncertain (Lee et al., 2021). A major ESS challenge is to improve detection and prediction of tipping points and integrate evidence from climate and biosphere science. For example, the most recent assessment of temperature thresholds for the risk of triggering an Amazon rainforest tipping point places the likely range at 3–5 °C GMST rise (Armstrong McKay et al., 2022). Ecologists, however, will question this assessment, based on the most recent assessment of ecological regime shift risks triggered by deforestation and loss of functional diversity, placing the tipping point at approximately 20–25% of overall forest loss (Lovejoy & Nobre, 2018). Today, the Amazon has reached 17% of forest loss, at 1.2 °C GMST rise.

Linking physical modeling with artificial intelligence applications can increase the precision in our understanding of the functioning of the entire Earth system. High-resolution Earth observations combined with machine learning methodologies for pattern recognition, are opening new avenues to predict and detect extreme events and non-linear changes in Earth system functioning, ranging from improved predictions of monsoon onset (Boers, 2021), to early warning assessment of critical transitions in the AMOC (Mitsui & Boers, 2021) and identifying early warning signals of tipping points (Bury et al., 2021).

One obvious candidate for such artificial-intelligence-based methodologies is the stubbornly wide equilibrium climate sensitivity (ECS) (of expected GMST rise resulting from doubling the CO_2 concentration), which has consistently remained at the unsatisfyingly wide range of approximately 1.5–4.5 °C for the past six IPCC assessments (Forster et al., 2021). Even though the conclusion today is that 1.5 °C can be ruled out, and recent work suggests the range may be narrowed to 2.6–4.1 °C (Sherwood et al., 2020), 16 climate models in the CMIP6 round still show ECS levels >4.7 °C (Zelinka et al., 2020). This is certainly a 'holy grail' in climate science, but the question is whether it is not rather a major challenge for Earth system science. What if, as a hypothesis, the Earth system is not regulated by one ECS function (believed to be linear and directly proportional to climate forcing (e.g. CO_2 concentration)), but by several. Could there be one (or several) bifurcation point(s) when Earth's interactions and feedback dynamics cause a phase shift from one ECS function to another (driven by new feedbacks, like cloud dynamics, albedo shifts, and biosphere feedbacks on land and in ocean), similar to what was proposed by Jim Hansen, who distinguished between fast and slow feedbacks determining different levels of ECS (shifting from 3 °C to 6 °C of average GMST rise with a doubling of CO_2) (Hansen et al., 2008)? A step change in climate sensitivity if Earth shifts from one regime to another (in terms of dominating feedback), could resemble the Earth system sensitivity discussed by Previdi et al. (2013).

Another holy grail for ESS remains the coupling of the human world with the biophysical Earth system. Will Steffen always defined this as 'whole Earth system science', referring to the Amsterdam declaration of the global environmental change science community (Moore et al., 2001), which declared Earth as a single self-regulating system comprising integrated human and biophysical components. The grand question is how Anthropocene insights from Earth system science can – or should – guide and perhaps steer transformations integrating people-planet pathways to a safe and just future for humanity within planetary boundaries. The Earth Commission is a first attempt to scientifically define and quantify not only the safe but also the just 'landing zone' for humanity on a stable and resilient Earth system (Rockström et al., 2021, 2023). Recent work attempts to develop a stylized model that enables human and environmental interactions to occur dynamically. In such World-Earth modeling frameworks environmental change not only causes impacts but also human response and potential social tipping points (Anderies et al., 2023).

Earth system science, having provided the public domain with evidence of the Anthropocene, Planetary Boundaries, and Tipping Points, has stimulated several strands of new research well beyond the Earth sciences. Will Steffen and Mark Stafford-Smith spurred the scientific debate on how the science on Planetary Boundaries profoundly impacts on equity and sustainable development (Steffen & Stafford Smith, 2013), which

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has been followed by the recent work by Gupta et al. (2023), defining and raising the new Anthropocene challenges of Earth system justice. These raise critical research questions that require continued focus, such as how to share the remaining ecological space (which all translate into budgets, just like the carbon budget, for water, nitrogen, phosphorus, and land) – across all Planetary Boundaries, in a fair and equitable way.

The frontier of ESS is increasingly connecting and integrating with economics, law, and political science. Recent work by economists and Earth system scientists, including Will Steffen, explored the implications for economic policies of steering world development as a 'Spaceship Earth' within Planetary Boundaries (Sterner et al., 2019). This review, together with the recent Dasgupta report on the Economics of biodiversity (Dasgupta, 2021), advocates for 'strong sustainability' measures in economics that respect Earth system guardrails, and the recent call for welfare economics within planetary boundaries (Sureth et al., 2023), provides both a basis and direction for future interdisciplinary Earth system research.

Inspired by the work of Elinor Ostrom on integrating the governance of the commons with global change (Steffen et al., 2011), there is a concerted scientific effort across disciplines to redefine the global commons in the Anthropocene (Nakicenovic et al., 2016). This first attempt resulted in the Global Commons Alliance (GCA), a global network with a mission to empower citizens, companies, and countries to become effective stewards of the global commons (https://globalcommonsalliance.org/). The research to redefine the global commons in the Anthropocene is ongoing. One of Will Steffen's final research endeavors points to the need to widen the scope from systems owned by nobody (and therefore by everybody, e.g. the high seas, Antarctica, and outer Space) to include all biophysical systems that regulate the state of the Earth System (upon which all citizens depend on) and ensure a habitable planet. This extended set was coined the 'Planetary Commons': clean air and water, biodiversity, healthy oceans, and a stable climate (Rockström et al., 2024). In bringing together ESS, global governance, and environmental law, Will's legacy of recognizing the existential interconnectedness of humans and the planet sits at the heart of the Planetary Commons idea.

The Planetary Commons opens up not only a research frontier for interdisciplinary Earth system research but also has major implications on governance and law, and the paradigm shift is already underway. In parallel with the steep rise in climate litigation cases around the world (total cases have doubled to over 2000 since 2015, with one-quarter of these being filed since 2020 (Setzer et al., 2022)), there is an increasing focus on exploring the legal framework arising from ESS insights into the Anthropocene, Planetary Boundaries and tipping point risks, with the state of knowledge recently synthesized in a book on Environmental Law and Planetary Boundaries (French & Kotzé, 2021). Will Steffen was actively engaged in exploring the implications of the latest findings in ESS for legal frameworks, for example, arguing for the formal declaration of the climate system, under a charter initiated by the United Nations and further developed by global civil society, as a Common Heritage for Humankind (Magalhães et al., 2016).

The governance challenges arising from ESS insights on rising global risks connected to equity and legal dimensions are profound (Biermann et al., 2012). It puts into question whether the nation-state is an appropriate unit for governing human development on Earth and brings forward new concepts, like how to govern the Planetary Commons, and how to equitably share ecological space on Earth. These Earth governance challenges also raise questions about the architecture for global governance, and how institutions like the Bretton Woods institutions (World Bank, International Monetary Fund) and the United Nations itself, can be adapted to the Anthropocene. Similar to the COVID-pandemic's 'Wuhan moment' (something goes wrong in one corner of the planet, disseminating rapidly across the entire Earth system), we need to be prepared for Earth system-related equivalents, if we experience abrupt shifts in major Earth system regulating tipping elements.

As it stands, ESS has delivered three key conclusions regarding future world development:

(1) a safe and just future for humanity on Earth is more than 'only' solving the climate crisis, it requires safeguarding the resilience and life-support systems of all Planetary Boundaries, in particular a functioning biosphere;
(2) meeting scientifically defined global sustainability criteria for climate, biosphere, and pollutants is a prerequisite for attaining the aspirational outcomes for world development expressed in the UN Sustainable Development Goals. Continued unsustainable development puts security, social stability, equity, and prosperity for the entire world at risk;
(3) nothing less than social transformation at a global scale (i.e. non-linear pace and scale-of-change processes) is required for a safe and just landing for world development within a stable Earth system.

This final point is receiving increasing attention from sustainability researchers and scenario modeling groups. Five years ago the Sustainable Development Solutions Network (SDSN) published the six transformation pathways that are necessary (and potentially sufficient) to meet all the 17 SDGs (Sachs et al., 2019). This was followed by the UN Sustainable Development Report, confirming the need for transformations, and identifying similar transformation pathways (focusing on human capacities, welfare economics, energy transition, food transformation, urban development, and governing the commons) (Messerli et al., 2019). Similarly, the Earth4All 50-year update of the Limits to Growth report identifies five 'turnarounds' – transformation pathways to deliver the 'SDGs within Planetary Boundaries' (Dixson-Declève et al., 2022) – and the Integrated Assessment Modeling (IAM) Community, building on the World in 2050 insights (Sachs et al., 2019), have advanced Sustainable Development Pathways (SDPs) to guide transformation scenario analyses, as a substitute to the Shared-socioeconomic pathways (SSPs) that have been guiding climate and energy scenarios (Soergel et al., 2021). This shows a direction of scientific momentum, with an integrated social and Earth system target space, well beyond climate, being set to guide transformation pathways for people and planet (van Vuuren et al., 2022).

The stepping stones laid by ESS: operational science-based targets for all Planetary Boundaries, policy guidance, and transformation pathways, describe the efforts of an interdisciplinary scientific endeavor to offer society the best possible opportunity to respond to the existential threats posed by ongoing global change. The scientific community has invested heavily in the task of translating fundamental science into implementable guidelines. Based on this evidence it forces the policy community to recognize the need to 'manage the planet'.

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Arriving at Earth system aligned governance, law and science-based targets, in a sense completes Will Steffen's scientific journey. He started at the biogeochemical and physical end of the scientific spectrum, focusing on understanding the stability and resilience of the Earth system, and ended with an integrated people-planet framework, with a profound interweaving of safety and justice, knowledge, and action. His legacy will guide us in the decisive years ahead.

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