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Scientists' warning to humanity for long-term planetary thinking on biodiversity and humankind preservation, a cosmic perspective

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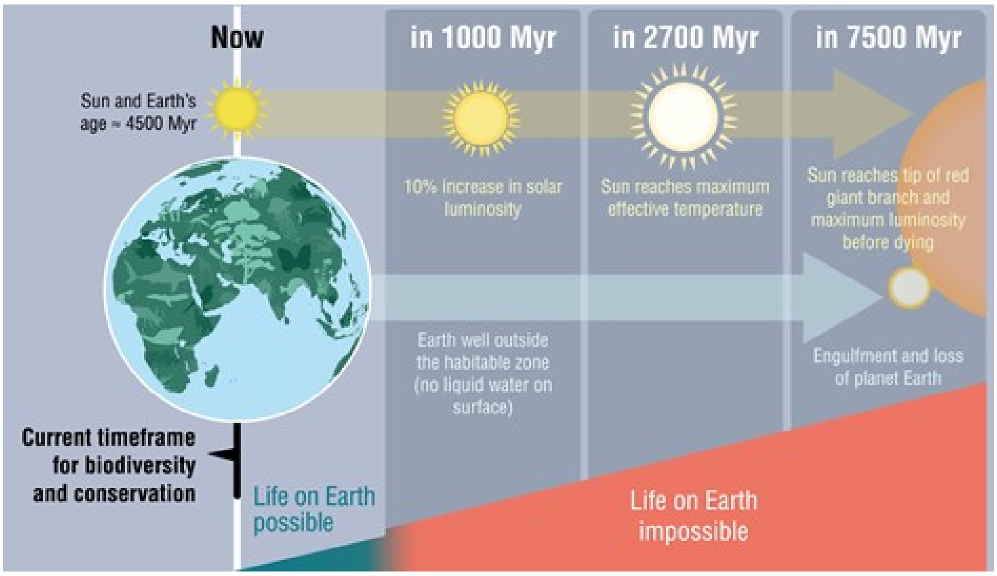
Issue Section: Viewpoint

"We are all made of stars," the song claims. Indeed, as Carl Sagan said, we are made of star stuff. But we often forget the message of unity ingrained in such reality. The typical narrow short-term perspective characterizing human planning, combined with self-interest, frequently leads to a tragedy of the commons where the very same resources essential for survival or prosperity are compromised or destroyed (Hardin 1968). Such selfish exploitation of common goods sits at the base of many current global problems, including the depletion of natural resources, accelerated climate change, and the loss of biodiversity. Fortunately, there is an increasing awareness of the importance of the natural environment, and an emerging paradigm shift is attempting to ameliorate the negative consequences of global problems for our children and subsequent generations. However, most if not all current plans are somehow shortsighted. For example, the Sustainable Development Goals adopted by the United Nations in 2015 set their targets for the year 2030. The United Nations Climate Change Conferences of the Parties implicitly or explicitly set their purposes for one or a few generations. The question is whether short-term goals and vision will be enough—or even adequate—to ensure the preservation of most life forms, including humanity, into the distant future. Although short-term targets are essential to trigger the necessary immediate action, shouldn't biodiversity preservation thinking and planning occur on a much longer time frame? If so, what is the appropriate time frame?

What does the future mean?

The current and next few generations are going to be critical to ensure that future generations inherit this planet in a healthy state. If nations manage to come together soon on global matters and we take the necessary actions to prevent the loss of biodiversity on Earth and to ameliorate other worldwide pressing issues (e.g., see table 1), the planet could, in principle, support life, roughly as we know it today, for thousands or millions of years. However, the Sun itself has an end. Astronomers estimate that, in about 5 billion years, the Sun will become a red giant that will absorb Earth (Schröder and Connon Smith 2008). But long before that, because of increased solar activity, within about a billion years, it is expected that life will not be possible on Earth (e.g., because of the evaporation of the oceans; Schröder and Connon Smith 2008). One billion years is about one-fourth of the time that life has been present on Earth; in other words, life on Earth is on its final fifth part of existence. This may sound dismal or fatalistic, but we instead see it as a reality that should spur a deeper sense of unity for humanity toward common goals; this reality reveals the need for thinking not only about global but also transglobal problems, as well as the need for collective and long-term commitments, to allow biodiversity and humanity to go on for as long as possible. The moment at which the conditions on our planet will make life impossible is far away, but we are heading toward it inevitably. When should we start paying attention, collectively, to such reality—1000 years before it happens, 10,000 years before? And when would it be too late? Shouldn't we start thinking about joining forces to allow humanity and as much biodiversity as possible to persist for as long as possible and to even, if feasible, persist beyond the existence of our local solar system? We advocate for the adoption of a cosmic perspective to conservation, including our own conservation (figure 1).

Figure 1.



Overview of current short-term and potential long-term (planetary and cosmic) perspectives on conservation. Predictions regarding landmark solar events and the moment Earth will be out of the habitable zone (based on whether the conditions on the planet allow the presence of liquid water on the surface), according to stellar models (Schröder and Connon Smith 2008) and superimposed on a graphical depiction of potential time frames for life on Earth and beyond. A graphical illustration of current time frames for biodiversity and humankind preservation is shown. Time points (in millions of years, Myr) and time frames are given for illustrative purposes and are out of scale.

Table 1. Relevant climate-related changes and responses, pressing environmental issues, and Earth systems processes.

Variable	Trend
Ozone depletors[a]	=
Freshwater resources per capita[a]	–
Reconstructed marine catch[a]	+
Dead zones[a]	+
Total forest area[a]	–
Vertebrate species abundance[a]	–
Carbon dioxide emissions[a,b]	+
Temperature change[a]	+

Human population[a,b]	+
Ruminant livestock[a,b]	+
Total fertility rate[b]	–
Per capita meat production[b]	+
World gross domestic product[b]	+
Global tree cover loss[b]	+
Brazilian Amazon forest[b]	–
Energy consumption—oil[b]	+
Energy consumption—coal[b]	+
Energy consumption—gas[b]	+
Energy consumption—solar and wind[b]	+
Air transport (number of passengers per year)[b]	+
Total institutional assets divested[b]	+
Per capita carbon dioxide emissions[b]	+
GHG emissions covered by carbon pricing[b]	+
Carbon price[b]	+
Fossil fuel subsidies[b]	+
Governments that have declared a climate emergency[b]	+
Carbon dioxide[c]	+
Methane[c]	+
Nitrous oxide[c]	+
Surface temperature anomaly[c]	+
Minimum Arctic sea ice[c]	–
Greenland ice mass change[c]	–
Antarctica ice mass change[c]	–
Glacier thickness change[c]	–

Earth's energy imbalance[c]	+
Ocean heat content change[c]	+
Ocean acidity[c]	–
Sea level change relative to 20-year mean[c]	+
Area burned in the United States[c]	+
Global tree cover loss due to fires[c]	+
Billion-dollar floods in the United States[c]	+
Extremely hot days relative to 1961–1990[c]	+
Climate change[d]	>
Biosphere integrity change[d]	>
Stratospheric ozone depletion[d]	*
Ocean acidification[d]	*
Biogeochemical flows (phosphorus and nitrogen cycles)[d]	>
Land system change[d]	>
Freshwater change[d]	>
Atmospheric aerosol loading[d]	*
Novel entities[d]	>

Note: [a]Environmental issues identified in the 1992 scientists' warning to humanity and for which Ripple and colleagues (2017) analyzed trends from 1960 to the 2010 decade. [b]Change in climate-related human activities from 1979 to present times, or [c]climate-related responses, as in Ripple and colleagues (2023). [d]Earth system processes for which planetary boundaries have been established and transgression levels examined (Richardson et al. 2023). The effects and consequences are broader than those shown. In addition to increased global temperatures, droughts, forest fires, extreme weather events, deforestation, altered biogeochemical cycles, local and global extinctions, and rising sea levels, for instance, there is increased soil erosion, loss of biodiversity, imbalances in the phenology and life cycles of organisms, disruption of biological interactions, changes in animal migration patterns, defaunation, increased biological invasions, loss of ecosystem services, in addition to social consequences such as increased chronic and emerging diseases, food crises and famine, displacement of human populations, increased migration, increased poverty and social inequalities, tensions over natural resources, threats to knowledge systems (including indigenous knowledge systems), economic losses, etc. Trends: +, increasing trend; –, decreasing trend; =, approximately unchanged trend; >, planetary boundary transgressed; *, planetary boundary within safe operating space. Simplified trends, from initial to end points, for the time period measured, are given.

The sooner a solution is sought, the better. We are currently in the middle of environmental and climate emergencies (Ripple et al. 2017, Ripple et al. 2023), but we may still be in time to prepare before entering a planetary emergency. An emergency is typically defined by two terms: the importance of the danger and the speed at which the danger arrives. However, a third critical factor is frequently neglected: the speed of the response that allows escaping or coping with the adverse situation. When it comes to the issue at hand, a distant point of no return for the maintenance of biodiversity or any form of life on Earth, the threat is clearly significant. In fact, this is probably the most important danger that humanity will face in its entire existence. However, the danger is quite far away, possibly quite a few millions of years away. But the development of a response capability (sustaining biodiversity up to that time and beyond) appears to be an extremely slow and complex process, because it requires many steps at collective levels, many global agreements and commitments, many technological breakthroughs, and a potentially very long time to test solutions. That is imperative to act now, to protect and bring biodiversity forward the next few generations, is beyond doubt, but it is also crucial to place our gaze on the longer time horizon.

A change for the better is needed, and it is possible through cooperation

In 1992, a group of more than 1700 independent scientists signed a manifesto warning that humanity was pushing the capacity of ecosystems and Earth to sustain life within acceptable parameters to the limit (Ripple et al. 2017). A second warning from 15,364 scientists 25 years later underscored the failure of nations to establish progress in solving most of the environmental and social problems previously identified and outlined aspects in which the situation worsened quite worryingly (table 1; Ripple et al. 2017). Scientists have provided ample evidence for these issues and other changes brought about or accelerated by human actions with pervasive negative effects on the climate, the ecosystems, and biodiversity, which, in turn, cascade to serious social consequences (table 1; Cardinale et al. 2012, Hoekstra and Wiedmann 2014, Díaz et al. 2019). Moreover, the dangers of surpassing several thresholds that delimit basic conditions for life (planetary boundaries) have also been established, and several of these boundaries have already been transgressed (table 1; Rockström et al. 2009, Richardson et al. 2023). Unfortunately, the list of environmental issues is long and growing. But we may be in time to solve many of the problems (Tallis et al. 2018, Díaz et al. 2019).

Humanity has previously demonstrated that cooperative decisions and actions can make a change for the better on a global scale. Examples include the expansion of renewable energy technologies, the commercial whaling moratorium, and the relative stabilization of the ozone layer as a result of policies regarding the use of substances that destroy it. Another example of progress by human cooperation that can be a landmark for future breakthroughs is the recent exceptional advancement in the development of nuclear fusion (Tollefson and Gibney 2022). The realization that net energy gain may be a reality through nuclear fusion offers hope for high-yield and relatively clean energy in the medium-term future. Concomitantly, obtaining clean, inexpensive, and abundant energy, as is promised by fusion reaction technology, could represent a quantum leap in space exploration potential. Such work on the shoulders of giants illustrates that humans can achieve great accomplishments when the right motivation and investments are in place. Regarding the issue at hand, the questions that require answers are these: Will humans have the motivation, forward-thinking, long-term investment and transnational cooperative attitude required to find solutions to an end-point problem? Or will we be forced to confront a need when it is too late?

Does it matter?

Many would wonder why we should care about and invest money in distant problems, when a long list of challenging problems predates us incessantly. This has been a recurrent question through human history. If investment is only allocated to pressing, current difficulties, humanity would be in a very primitive, archaic, and undeveloped state. Neil deGrasse Tyson puts it very well with an analogy: “To gain insight, let's rewind thirty thousand years and eavesdrop on our ancestral cave dwellers. Those among them with the urge to explore decide to consult the elders, saying, ‘We want to see what's beyond the cave door.’ The elders are wise. They caucus among themselves, weighing what they think are the risks and rewards, and reply, ‘No. We must first solve the problems of the cave before anyone ventures beyond’” (DeGrasse Tyson 2022). With an exclusive focus on solving imminent problems, which are and will be always around, we would remain unaware that, outside the cave, there may be solutions to solve the problems within the cave.

Some have considered the end of the human lineage, mammals, and most life reflecting geologic and cosmic time scales that are beyond comprehension. If one accepts that we are but a small planet on the edge of a galaxy, with unimaginably more galaxies and planets (around a couple of trillion galaxies following the latest estimations, with each galaxy containing several billion stars and with many stars hosting planets), what does life's extinguishment on Earth really matter? We think that it does indeed matter, if only from a perspective of keeping *maximal cosmic biodiversity*. We also have a moral obligation to try to remedy future problems that may threaten the existence of humanity and life itself. And there are additional nonutilitarian and utilitarian reasons unforeseen today. Regarding nonutilitarian motivations, the possibility of intelligent life throughout the universe is a subject of active debate among astrobiologists (e.g., see Mahecha 2016, Frank 2018), but thus far, there is no scientific evidence of other life in the known universe. Allowing for the only current evidence of life in an inert universe to vanish is therefore unacceptable, if only for ethical reasons. Our duty as a civilization is to give empirical testament of the process of evolution of life on Earth. Even in the event of the discovery of new forms of life, we should shy away from inaction and lame attitudes and do our bit as a civilization to ensure disseminating the empirical example of the story of life on Earth. Second, from a utilitarian standpoint, the preservation of biodiversity on Earth and beyond is a necessity to give our species and the rest of existing biological diversity a life-supporting system. This utilitarian view may also have nonutilitarian consequences, because other extant or future emerging civilizations might be helped by the understanding of our own biological or cultural evolution processes. Under both nonutilitarian and utilitarian views, a plan to maintain biodiversity indefinitely would be required.

Long-term planetary thinking

Our current generation is witnessing a shift in the collective consciousness of the value of biodiversity and nature. But we must go further. We must have a more distant view of conservation objectives (figure 1). It is perhaps time to think that, at some point, we will need an intergovernmental panel on the long-term future of biodiversity and humanity. We need a planetary plan. The idea of a continuous unity for humankind throughout time has been conceptualized and advocated previously (box 1). However, long-term planetary conceptions for maximal (including humanity) biodiversity conservation are largely lacking (box 1).

Box 1. Unity of humankind through time.

Arguably the most prominent defender of unity of humankind through time was Carl Sagan. The description of our planet as Spaceship Earth by Buckminster Fuller is also relevant when considering a planetary conception of humanity. In his view, humanity constituted a group of passengers aboard Spaceship Earth, analogous to a ship's crew who must cooperate in order to keep the ship working. More recently, Neil DeGrasse Tyson and Adam Frank provided enlightening cosmic perspectives on civilization (Frank 2018, DeGrasse Tyson 2022), and the architect Benjamin Bratton advocates in *The Terraforming* for a planetary conception focused on rethinking urban design without forgetting ecosystem preservation (Bratton 2019) and suggests that a Copernican turn is needed in the context of inhabiting Earth. However, long-term planetary conceptions for maximal biodiversity conservation are mostly lacking. The half-Earth suggestion of E. O. Wilson to set aside in reserve at least half the world (Wilson 2016) is arguably the closest initiative attuned with a long-term vision for biodiversity conservation at a global scale. More recent initiatives such as the Global Commons Alliance (https://globalcommonsalliance.org), the Earth Commission (https://earthcommission.org), and Future Earth (https://futureearth.org) have built on this need for global conception, and both the Global Deal for Nature and the Global Safety Net have been proposed as a plan on the basis of scientific evidence for the preservation of life on Earth (Dinerstein et al. 2019) and as an accompanying global-scale analysis of key areas for biodiversity and climate resilience that can serve to inform land use planning (Dinerstein et al. 2020), respectively. We completely agree with Dinerstein and colleagues (2020) that “The level of planning and foresight that is needed to properly scale nature conservation requires the emergence of a worldview that embraces the notion of stewardship at a planetary scale.” All these plans appropriately set or support time-bound milestones (e.g., to conserve at least 30% of the Earth's surface by 2030 and 50% by 2050 or earlier; Baillie and Zhang 2018). We also agree with short- or intermediate-term targets for these actions, because they are mostly needed in the face of the current planetary situation, but we emphasize that they are not in conflict with the longer-term vision for conservation biology that we advocate in this article.

Conclusions

If we continue with the business-as-usual model, we will be facing, sooner or later, the biggest tragedy of the commons in human history. We can reverse this trend. Humanity needs a sense of unity transcending shortsightedness. If there is a common goal to preserve life and humanity on planet Earth, there is a tangible fundamental reason for us to start working together. Furthermore, we should aim for the common goal of preserving biodiversity even beyond Earth's life, which is finite, inexorably, because of the physics of the solar system (figure 1). Ironically, we need a Copernican turn in the way we consider long-term biodiversity conservation, to take us away from the heliocentrism to which Copernicus and Galileo so properly led us to. We need a starting point to set more ambitious objectives regarding the future of biodiversity. Objectives at short time scales (years, decades, a few generations) are typically set up by governments and decision-makers, and these objectives are needed for tangible actions, but longer-term objectives are also needed. Ensuring that known and not yet described by science biodiversity carries on for as long as possible can be the most important common goal humans would ever face.

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References cited

Baillie J, Zhang Y-P. 2018. Space for nature. *Science* 361: 1051–1051.
Google Scholar Crossref PubMed WorldCat

Bratton BH. 2019. *The Terraforming*. Strelka Press.
Google Scholar Google Preview WorldCat COPAC

Cardinale BJ et al. 2012. Biodiversity loss and its impact on humanity. *Nature* 486: 59–67.
Google Scholar Crossref PubMed WorldCat

DeGrasse Tyson N. 2022. *Starry Messenger: Cosmic Perspectives on Civilization*. Holt.

Díaz S et al. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 366: eaax3100.
Google Scholar Crossref PubMed WorldCat

Dinerstein E et al. 2019. A global deal for nature: Guiding principles, milestones, and targets. *Science Advances* 5: eaaw2869.
Google Scholar Crossref PubMed WorldCat

Dinerstein E et al. 2020. A "global safety net" to reverse biodiversity loss and stabilize earth's climate. *Science Advances* 6: eabb2824.
Google Scholar Crossref PubMed WorldCat

Frank A. 2018. *Light of the Stars: Alien Worlds and the Fate of the Earth*. Norton.
Google Scholar Google Preview WorldCat COPAC

Hardin G. 1968. The Tragedy of the Commons. *Science* 162: 1243–1248.
Google Scholar Crossref PubMed WorldCat

Hoekstra AY, Wiedmann TO. 2014. Humanity's unsustainable environmental footprint. *Science* 344: 1114–1117.
Google Scholar Crossref PubMed WorldCat

Mahecha DS. 2016. Evolution through the stochastic dyadic Cantor Set: The uniqueness of mankind in the universe. *International Journal of Astrobiology* 15: 319–331.
Google Scholar Crossref WorldCat

Richardson K et al. 2023. Earth beyond six of nine planetary boundaries. *Science Advances* 9: eadh2458.
Google Scholar Crossref PubMed WorldCat

Ripple WJ et al. 2023. The 2023 state of the climate report: Entering uncharted territory. *BioScience* 73: biad080.
Google Scholar WorldCat

Ripple WJ, Wolf C, Newsome TM, Galetti M, Alamgir M, Crist E, Mahmoud MI, Laurance WF. 2017. World scientists' Warning to humanity: A second notice. *BioScience* 67: 1026–1028.
Google Scholar Crossref WorldCat

Rockström J et al. 2009. A safe operating space for humanity. *Nature* 461: 472–475.
Google Scholar Crossref PubMed WorldCat

Schröder K-P, Connon Smith R. 2008. Distant future of the Sun and Earth revisited. *Monthly Notices of the Royal Astronomical Society* 386: 155–163.
Google Scholar Crossref WorldCat

Tallis HM et al. 2018. An attainable global vision for conservation and human well-being. *Frontiers in Ecology and the Environment* 16: 563–570.
Google Scholar Crossref WorldCat

Tollefson J, Gibney E. 2022. Nuclear-fusion lab achieves "ignition": What does it mean? *Nature* 612: 597–598.
Google Scholar Crossref PubMed WorldCat

Wilson EO. 2016. *Half-Earth: Our Planet's Fight for Life*. Liveright.
Google Scholar Google Preview WorldCat COPAC

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REVIEW ARTICLE OPEN

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Radical changes are needed for transformations to a good Anthropocene

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The scale, pace, and intensity of human activity on the planet demands radical departures from the status quo to remain within planetary boundaries and achieve sustainability. The steering arms of society including embedded financial, legal, political, and governance systems must be radically realigned and recognize the connectivity among social, ecological, and technological domains of urban systems to deliver more just, equitable, sustainable, and resilient futures. We present five key principles requiring fundamental cognitive, behavioral, and cultural shifts including rethinking growth, rethinking efficiency, rethinking the state, rethinking the commons, and rethinking justice needed together to radically transform neighborhoods, cities, and regions.

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RADICAL DEPARTURES

The scale, pace, and intensity of human activity on the planet[1] is driving global biodiversity and ecosystem decline[2], fundamentally altering earth's climate system[3], and increasing social and economic global connectedness[4] in ways that threaten stability, resilience, and sustainability of local and regional human and ecological systems[5]. These patterns suggest we are living in what has been described as the Anthropocene Epoch[6] characterized by rapid and fundamental human-driven alterations of earth systems across the globe[7]. These major shifts to the stocks and flows of human life-support systems[8,9] challenge sustainability at any scale without fundamental and radical transformations in human activities and supporting financial, legal, political, and governance systems[10].

To shift the human enterprise toward a sustainable relationship with, and within, the earth system requires much more than small tweaks and incremental change[11]. Instead, it will require radical departures from the status quo[8,12–16] where the complex system of intertwined sustainability challenges[17] are confronted in order to shift multiple unsustainable trajectories toward 'good' Anthropocenes[18] where normative goals for sustainability are achieved[19] and political and economic power structures deliver the common good[20]. Radical change necessitates investments in knowledge, technology, institutions, and modes of business, as well as personal and socio-cultural behavior and meanings. Unlike existing approaches to transformation, radical change seeks to drive major shifts in understanding and actions across a broad range of diverse communities that can lead to shifts at both individual and organizational levels[21]. Tendency to focus on biophysical or economic quantification of the couplings between society and technology or society and ecological systems can overlook a critical element of radical thinking—the necessity to consider underlying social drivers such as capitalist competition and unequal power relations in ways that do not reproduce dominant growth and efficiency logics[22]. The radical changes required for transforming pathways toward 'good' Anthropocenes thus require more holistic, intertwined social–ecological–technological systems (SETS) understanding and approaches[23].

We propose five key principles as necessary preconditions for societal transformation to achieve a good Anthropocene, one that is just, equitable, resilient, and sustainable. These principles include rethinking growth, rethinking efficiency, rethinking the state, rethinking the commons, and rethinking justice. We illustrate the potential to coordinate actions across five principles with the concept of connective tissues to ensure that dynamic linkages and feedbacks among interacting social, ecological, and technological–infrastructure system domains are considered and managed for driving transformation. In doing so, we attempt to reframe the dominant dystopian futures narrative to provide a conceptual framework and example case studies demonstrating how systems-level transformation can be initiated. We seek to open the door to new, more radical, and urgently needed systems-based policy, planning, design, and management approaches intrinsically based on the obligation to deliver positive, desirable futures.

Accelerating challenges

Globally, greenhouse gas emissions continue to increase, global ice has been rapidly disappearing, ocean heat content, ocean acidity, and sea-level rise are trending upward, all while human population, world GDP, air transport, and fossil fuel subsidies exponentially increase[5]. Moreover, average abundance of native

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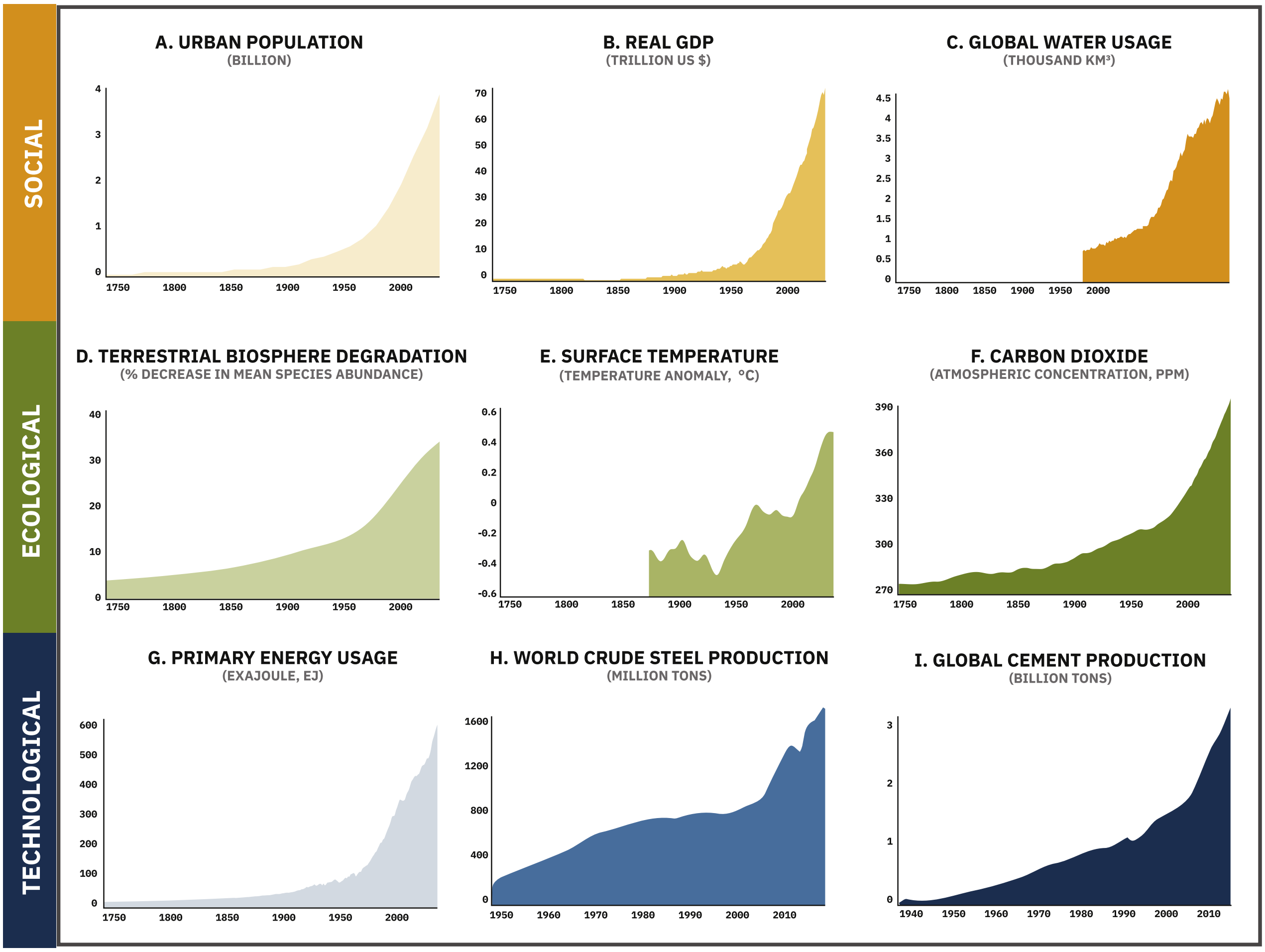

Fig. 1 The great urban acceleration? Global urban and related trends are accelerating with cross-cutting impacts on human and earth systems, **A** Global urban population data according to the HYDE database. Data before 1950 are modeled. Data are plotted as decadal points. **B** Global real GDP (Gross Domestic Product) in year 2010 US dollars. Data are a combination of Maddison for the years 1750 to 2003 and Shane for 1969–2010. **C** Global water use is sum of irrigation, domestic, manufacturing, and electricity water withdrawals from 1900 to 2010 and livestock water consumption from 1961 to 2010. The data are estimated using the WaterGAP model. **D** Percentage decrease in terrestrial mean species abundance relative to abundance in undisturbed ecosystems as an approximation for degradation of the terrestrial biosphere. **E** Global surface temperature anomaly (HadCRUT4: combined land and ocean observations, relative to 1961–1990, 20 year Gaussian smoothed). **F** Carbon dioxide from fern and ice core records (Law Dome, Antarctica and Cape Grim, Australia) (deseasonalized flask and instrumental records); spline fit. **G** World primary energy use. 1850 to present based on Grubler et al.[147], 1750–1849 data are based on global population using 1850 data as a reference point. **H** Crude steel production in 66 countries globally, in millions of tons, based on World Steel Association, 2015. **I** Global cement production with adjusted Portland cement shipment in billion tons. Plot styles are adapted from Steffen et al.[148].

species in most major land-based habitats has fallen by at least 20%, mostly since 1900. More than 40% of amphibian species, almost 33% of corals and more than a third of all marine mammals are threatened by human activities[2]. At the same time, rapid urbanization has driven exponential consumptive demand for natural resources, energy, and built infrastructure, largely using outmoded 20th century design and construction techniques[24] (Fig. 1). This demand has generated interdependent and cascading risks, and threatens the resilience of human, ecological, and infrastructure systems, especially in urban areas where the majority of humans and infrastructure are concentrated[25–29].

The future is therefore unsurprisingly dominated by dystopian narratives[30] that stem from business-as-usual projections of current trends in population, economic, and urban growth (Fig. 1). These narratives exist in prominent future scenarios from global bodies such as the IPCC, IPBES and other[31] economic scenarios, and which represent multiple future Anthropocene-related risks, such as from weather-related extreme events (e.g., drought, heat waves, coastal storms, and fires)[32]. Extreme events do not pose only future risks but are already impacting human and ecological communities[33] with complex local, regional, and global feedbacks that challenge human ability to innovatively manage the earth system at scale and alter current negative social and environmental trajectories toward more positive, desirable futures. While a return to past functionality or global climate has limited prospects[34,35] owing to its systemic complexity and our fundamental alteration of its dynamic stability, creating, owning, and acting upon positive visions that counter dystopian narratives is possible and critical to chart pathways, create motivation, and drive action in the present[16,17,30]. However, visions alone are insufficient. More radical transformative thinking is required that provides systemic leverage, actionable ideas, and supportive governance processes to develop pathways for how local, regional, and national innovations can be upscaled to drive global-scale sustainability transformations. Fundamental, and even radical transformations will require creative ways of connecting different types of actions and feedbacks across subsystems to promote positive tipping points[36].

A good Anthropocene

There is much debate on defining the Anthropocene. We follow Hamilton (2016) and consider the Anthropocene as the 'recent rupture in Earth history arising from the impact of human activity on the earth system as a whole'[37]. Anthropocene risks emerge from globally intertwined social, ecological, and technological drivers that exhibit cross-scale interactions from the local to the global[37]. As we improve ways to understand these complex interactions not only within and among systems, but also among resilience and sustainability initiatives, it is becoming clear that to alter earth system trajectories and create alternative pathways toward a better Anthropocene, we need more fundamental and radical transformations that can deliver systemic changes[19,23,28,38]. We define a 'dystopian Anthropocene' as one that broadly mirrors the present, where the current status quo is maintained into the future with human societies facing rampant inequality, unacceptable social and environmental injustice, economic models and development trajectories focused on growth, law used as a reactive tool to cement the status quo, and environmental ills from human-caused pollution, climate change, and ecosystem degradation unchanged or worse. In contrast, we define 'good' Anthropocenes as ones where these trajectories are reversed and the future is environmentally just, socially equitable, ecologically healthy, socially, ecologically, and technologically resilient and sustainable at all scales. To achieve the future we want will require radical changes in human cognition, behavior, and cultural norms but we argue, with others[39–42] that such change can begin by scaling up 'seeds' of positive futures that already exist across the globe. Scaling up such seeds, together with articulated pathways to the future that engage with diverse values, worldviews, knowledge systems, power structures (both political and financial), and scales, can promote transformations toward normative societal goals[43]. Such seeds of good Anthropocenes can include social movements, new technologies, economic tools, projects, organizations, or new ways of acting that support a prosperous and sustainable future, considering external drivers and cross-scale dynamics, as well as internal drivers of these interrelated systems. Transformation, however, requires more than scaling up current initiatives and innovations, and also a fundamental incorporation of systems approaches in order to be impactful and to have potential to scale at the level needed to meet global challenges facing not only human society, but non-human actors as well.

It is systems all the way down

Social–ecological systems literature demonstrates that social and ecological systems are linked through feedback mechanisms, and display resilience and complexity[28,44,45]. Transitions in these literatures are commonly considered as co-evolution processes that require multiple changes in socio-ecological or socio-technical systems or configurations[42]. Modeling approaches have been developed to explain how different policy mixes influence social–ecological[18,46] or social–technical change[47]. However, existing approaches rarely consider the dynamic interrelationships across the full suite of SETS in a holistic manner to inform radical change. We utilize the SETS conceptual framework as a useful starting point for examining whether systems interactions are considered in transformation initiatives because this framework can help to understand the interlinkages or 'couplings' between elements of SETS[32,37,48–50]. The SETS conceptual framework (Fig. 2) complements recent scholarship in social–technical or social–ecological systems research[51,52]. SETS has been used in multiple cases and projects to enable examination of the interactions and interdependencies of human, environment, and technological–infrastructure interactions[48–57] and can be a way to analyze the potential of positive seeds of transformation to grow toward larger scale and more radical changes. The 2020 U.S.

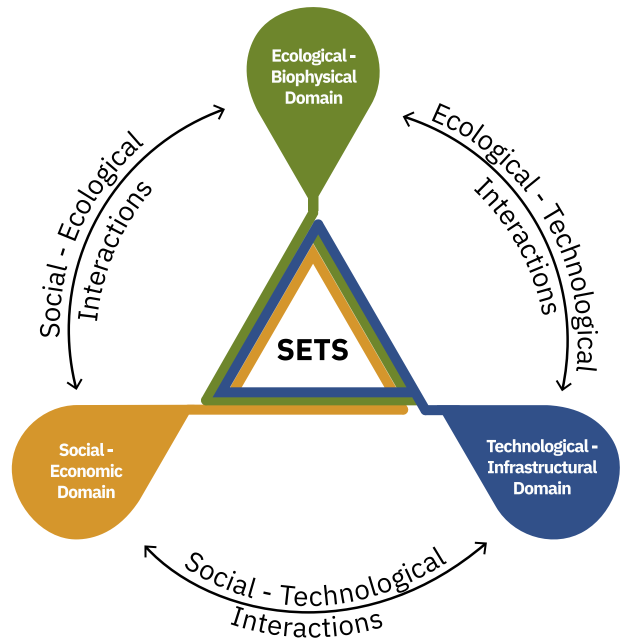

Fig. 2 The social–ecological–technological systems (SETS) conceptual framework. The SETS framework emphasizes the social–economic, ecological–biophysical, and technological–infrastructural couplings that drive systems processes and patterns in an increasingly interconnected world at local and global scales (adapted from McPhearson et al.[49] and Depietri and McPhearson[58]). Interactions across S, E, and T domains are diverse and may include abroad range of, e.g., coupled human–environment dynamics, coupled climate–infrastructure dynamics, and institutional–technological dynamics among many others. Below we describe multiple examples of S-E, S-T, and E-T interactions as 'couplings'.

National Science Foundation's call for Sustainable Regional Systems research argues for SETS as the conceptual foundation to anchor systems approaches that can deliver sustainability across urban and rural interlinked systems[50]. SETS thus aims to overcome the limitation of a purely socio-technological approach which tends to exclude ecological functions, or of social–ecological approaches which may overlook critical roles of technology and infrastructure, all of which are fundamental constituents and drivers of, e.g., urban system dynamics[58]. The SETS framework can therefore broaden the spectrum of the options available for intervention[48] and is a useful foundation to explore sustainability plans, actions, and initiatives, while identifying barriers to change within existing actions, governance frameworks, economic constraints, and value systems.

Here we use the SETS framework to examine the interdependencies across system domains within five key interrelated principles for rethinking human activity on the planet. We suggest that these five principles are among the preconditions for the radical transformations necessary to shift human–environment interactions toward planetary sustainability. Our use of a SETS framework focuses on three main system couplings (Fig. 3 and Table 1): (1) social–ecological (S-E) couplings refer to human–nature or social–ecological relationships, feedbacks, and interactions, such as how urban nature provides ecosystem services to support human health and wellbeing[59] or linkages between stewardship of urban green spaces and ecosystem change[19,60], (2) social–technological (S-T) couplings refer to the ways in which technology and human social systems interact such as providing ability to communicate globally through social media[61] or the dependence on technological infrastructure to facilitate dense

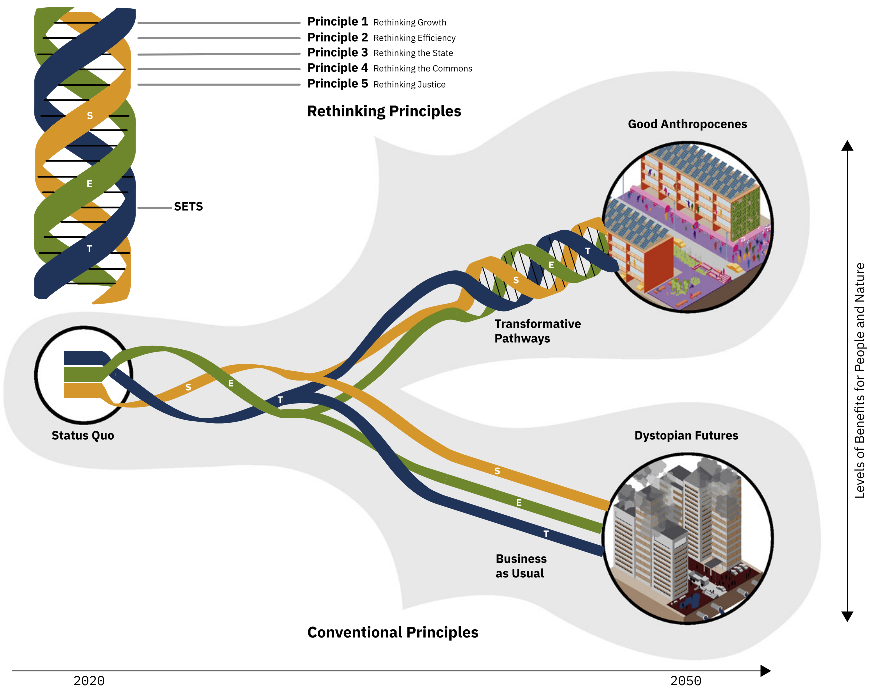

Fig. 3 Rethinking principles define transformative pathways that can steer societies toward good Anthropocenes. The *x*-axis represents time and the *y*-axis the degree of transformative change required. The pathways consist of a triple-helix structure containing SETS that are inter. Rethinking principles both exist across SETS and attract transformative pathways toward good Anthropocenes away from the status quo, enabling potential dystopian futures to be avoided. The rethinking versus conventional principles describe opposite societal forces pulling the interpretation of the five principles into opposite directions. The positive rethinking principles pull toward diverse pathways toward good Anthropocenes, and conventional principles pull toward business-as-usual pathways, maintaining status quo societal underpinnings toward dystopian futures. Rethinking principles are illustrated as connective tissue enabling tight coupling and structure of the SETS helix needed for transformation, with multiple nodes demonstrating opportunities for interconnection, integration, and multifunction that can enable systemic transformations to achieve good Anthropocenes.

human living in cities; and (3) ecological–technological (E-T) couplings refer to the different ways in which climate and biophysical systems impact technology such as wild fires which cause power outages or rising temperatures driving increased energy use for cooling technology in buildings which in turn contributes to the urban heat island[62]. The SETS couplings are not limited to these examples, but rather provide a starting point for more holistic systems approaches in developing and scaling up sustainability initiatives at multiple scales.

We cannot solve complex challenges with simplistic approaches. We need more systemic experimentation and learning making it important that relevant SETS couplings be systematically identified, understood, and managed to address climate resilience opportunities or to transform interdependent systems to be more sustainable. We will also never be able to fully understand complex systems given constant change, dynamic feedbacks, and non-stationarity which creates uncertainties that can be reduced, but not eliminated. Thus, the SETS framework provides a middle ground for expanding systems thinking in multiple domains, while providing a starting point from examining linkages between S, E, and T domains in SETS couplings to build up ability to consider interactions, feedbacks, trade-offs, and synergies that exist within any subsystem, also, interacting across systems. We suggest that siloed efforts at transformation in only one S, E, or T domain without considering at minimum S-T, S-E, and E-T couplings and better S-E-T interactions, will ultimately fail precisely because they overlook the interdependent and complex nature of any SETS process, pattern, or dynamic in the Anthropocene, where humans and their technology dominate and undermine natural planetary processes[8,63,64].

Five principles for transformation

While SETS provides a framework for the application of a systems approach to defining options for managing Anthropocene risks, specific pathways and radical principles for realizing a good Anthropocene and operationalizing the SETS approaches are still needed, also, articulation and exploration of the connective tissues that can unite disparate transformation approaches across SETS. We propose five key rethinking principles based on an interdisciplinary literature foundation that recognizes the complexity and scale of the challenges facing humanity. We specifically consider the importance of core principles rethinking growth, rethinking efficiency, rethinking the state, rethinking the commons, and rethinking justice (Table 1) with reference to the S-E, S-T, and T-E couplings that need to be examined together in a specific intervention or initiative (Fig. 3). We provide examples of couplings for each principle, while also acknowledging that these examples are not entirely independent of other couplings, nor fully systems approaches, or even radical enough to achieve transformations at the scales needed. However, where case studies exemplify action on multiple principles, they are instructive of how we can begin to implement all rethinking principles and systems approaches for change. Examples are, however, 'seeds' that have potential to be replicated or scaled up, and more importantly, provide examples of how couplings and addressing core rethinking principles can help to set local urban SETS on more transformative pathways. Our framework and the five key principles are intended to reframe scholarly debate on sustainability transformations to a systems-oriented, adaptive, and relational perspective respecting the interlinkages across SETS. The core innovation of this perspective is not that any example or principle is in itself adequately novel or transformational, rather

Table 1. Rethinking principles and their manifestations in SETS couplings.

Rethinking principles	Relevance to SETS couplings		
	Social–technological (S-T)	Ecological–technological (E-T)	Social–ecological (S-E)
Rethinking Growth is about viewing degrowth as an opportunity to slow exploitative economies and co-create a value proposition that incorporates the value–nature nexus accounting for long-term sustainability, social and ecological benefits. It challenges the maldistribution of income and power, and encourages value systems and economies that are regenerative, environmentally sustainable, localized, and return value to the local community.	Leapfrogging with disruptive technologies that include impact and blended finance, microfinance, and crypto-finance to leap ahead of the barriers around implementing more equitable approaches for how finance and investment is delivered to communities (e.g., micro- and crypto-finance; micro-grids; localized food and water management).	Recognizing a wider set of relational and intrinsic values within technological developments so that no one falls short on life's essentials while ensuring that collectively we do not overshoot our pressure on Earth's life-support systems and planetary boundaries (e.g., Waka Waka Share the Sun project: lighting up millions of lives around the world)	Enhancing human–nature value shifts, and changing the valuation process broadening it to become more inclusive, rather than exclusive (of costs and impact) (e.g., NorWest Community Co-op in Winnipeg, Canada: promoting community advocacy, gender diversity, healthy eating, and generally bringing people together to grow, cook, share, and advocate for good food for all).
Rethinking Efficiency involves recognizing that the short-term and segmented pursuit of efficiency can not only harm society but also hinder transformative changes. We argue for effective and social and ecological beneficial use rather than efficiency.	Establishing new technologies with less emphasis on allocative and productive efficiency and more emphasis on the fair distribution of goods, also taking externalities into account (e.g., community solar initiatives in Australia).	Developing new technologies for cyclical closed-loop systems mimicking nature to able to effectively grasp the ecological efficiency of systems (in terms of how material recycle and energy flows between trophic levels), and set resilience indicators to match these levels (e.g., Parisculteurs, France: establishing closed-loop urban green roofs across Paris).	Involving citizens in urban open space governance, moving beyond the human as co-production but rather encompassing human and non-human interactions (e.g., ByBi, Denmark, and circular economy initiative, Copenhagen).
Rethinking the State involves viewing the state as the one that not only reacts to market failures with regulation, but is also an actor that can support initiatives at local and global levels (e.g., inspire markets and people, give societal direction, build capacity, mediate and resolve conflicts, and institutionalize best practices).	Recognizing within law the social consequences of AI and other smart solutions that is pushing rapid development in information technology (e.g., General Data Protection Regulation, European Union).	Providing incentives for new technologies that alleviate the ecological stress caused by human activity and help accumulate revenue. E.g., technology related to water status, water purification, water efficiency, flood management, and energy production (e.g., underwater robots plant coral 'babies' to repopulate the Great Barrier coral reef).	Legitimate and effective governance solutions being informed by market and local actors, as well as government-imposed direction and insights which can take into account the needs and rights of the non-human (e.g., Te Urewera Act, New Zealand: recognizing that a forest has the same legal rights as a citizen).
Rethinking the Commons refers to changes in the way we understand, govern, and use physical, cultural, and intellectual commons to ensure their long-term availability to all members of a society. Emphasis is placed on building trust in local government and the experimentation process, learning from social innovation.	Re-emphasizing the role of public infrastructure as shared spaces, resources, and transportation services that can be provided for common use and more equitably (e.g., Wrocław's, Poland: integrated, holistic, and innovative approach to sustainable mobility planning, supported by neighborhood planning and citizen engagement).	Making digital environmental data available for common use as is increasingly provided from sensors, satellites, social media, and crowdsourcing (e.g., Crowdsourcing Sustainability, helping to reverse global warming).	Providing opportunities for the co-existence of nature and humans in public spaces; fostering stewardship and shared responsibilities (e.g., Rethink Food, New York, was founded to use America's food excess to feed the hungry).
Rethinking Justice is concerned with the relationships between people and place, and the range of knowledge and experiences of environmental change that impact everyday life for individuals and communities. It is also about building adaptive capacity to manage environmental change and advance ecological justice, which evokes notions of reciprocity and care for humans and non-human entities and so requires the	Promoting intergenerational and intersectoral justice through our technological infrastructure (e.g., create digital spaces that enable authentic engagement by diverse interest groups, including quieter voices in society).	Encouraging participatory approaches to digital technologies which provide novel opportunities to investigate elements of procedural and distributional justice (e.g., Maptionnaire participatory mapping tools, Helsinki, Finland).	Facilitating new forms of hybrid systems and human–nature connections that promote equal and fair access to blue-green spaces. All living beings should have a right to access, occupy, and use urban space and exercise democratic control over the current and future development of the city (e.g., The Living Pavilion: transdisciplinary project that brought together Indigenous knowledge, ecological science, sustainable design, and participatory arts on a temporary

Table 1 continued

Rethinking principles	Relevance to SETS couplings		
	Social–technological (S-T)	Ecological–technological (E-T)	Social–ecological (S-E)
exploration of new regulations and procedures for recognizing and managing for the rights of the non-human.			ecological site at the University of Melbourne)

that bringing SETS perspectives and these five principles together can begin to provide the needed development of conceptual and methodological pathways for the radical changes we need to achieve a common and inclusive good for human and non-human species. We challenge planners, decision-makers, regulators, and governments at multiple scales to work together across system domains to develop more integrated strategies to achieve shared normative visions including the Sustainable Development Goals[65,66]. Civil society, active citizen groups, local government, local business, and the wider private sector replete with synergistic actions all have an important and obligatory role[66] in implementing the principles presented here. Processes of mosaic governance including governance sensitive to a diversity of forms of active citizenship, and cross-sectoral industry and government networks[67] cut across all principles with a view toward building shared ownership and transcending entrenched paradigms[38] while shifting toward good Anthropocenes.

Principle 1: Rethinking growth

Existing economies are GDP focused[11] and cost–benefit analysis driven with poor inclusion of externalities[68], which promotes resource exploitation without full non-tradable cost/value inclusions[69], and which are part of driving global crises[31]. Corporate sector interests in league with political entities are so powerful[10] that push back from transformative ideas is stymied because perpetual profit through an economic growth model is entrenched in policy, law, business, and global economies[22]. The principle of rethinking growth, we argue, involves, for example, the development and widespread adoption of new ecologically based business models, such as recognition of the co-benefits associated with investment in nature[31,70] and the multiple values of nature. This principle necessitates accounting for not only the social (non-dollar) value of natural capital, human capital, and produced capital[71], but also more diverse values of nature grounded in ethics of care and reciprocity of human–nature relationships[72]. Rethinking growth means viewing degrowth[73–76] as an opportunity to slow exploitative economies based on shareholder capitalism, and co-create a value proposition that takes a broader stakeholder view incorporating the value–nature nexus accounting for long-term sustainability, social and ecological co-/dis-benefits, and that can drive global trends to deliver the SDGs[77,78]. While we acknowledge that ecological economics[79] and limits to growth theory[80] has been around since the 1970's, these theories have not been applied at relevant scales (local to global) nor with the necessary governance framing to achieve the required radical societal transformations. We argue for rethinking growth particularly where economic utilization and adoption is viewed through the market–government collusive lens focussed on economic expansionary growth rather than planetary ecological limits and human well-being ensconced as the major driver for decision-making. Rethinking growth toward good Anthropocenes also requires incorporating alternate indicators of success other than GDP, profits, shareholder capitalism, and regulatory framing in order to counter the influence of a corporate oligarchy that has become increasingly global, politically influential, and financially unaccountable[10]. For example, a systemic shift from competitiveness scarcity and bottom line profit-driven, resource-depletive production processes, to ecological system limits, health, and wellbeing would be an important starting point[17,81]. Similarly, this principle means also creating a stronger community focus with shared decision-making such as collaborative abundances, participatory budgeting, promoting equity, recognition of altruistic outcomes, and improving opportunities for citizens[82] to become more effective collaborators and decision-makers[83].

New approaches to rethinking growth in urbanization are provided by example of the Cheonggyecheon (which translates to 'clear valley stream') Restoration Project in Seoul, South Korea. This project is a large-scale urban greening effort in a densely populated city. The Cheonggyecheon Restoration Project complemented traditional valuation with considerations of social and ecological values over longer time spans by focusing on large-scale urban regeneration including removing a two-tier overpass and landscaping the river channel beneath it. The rejuvenated river system provides flood protection for up to a 200-year flood event, increased overall biodiversity by 639% (between 2003 and 2008), and reduced the urban heat island effect with temperatures along the stream 3.3–5.9 °C cooler than on a parallel road four to seven blocks away. This effort rejuvenated transportation and contributed to a 15.1% increase in bus ridership and 3.3% in subway ridership in Seoul and reduced small-particle air pollution by 35%[84]. Yet, we include this example not only because the urban greening represents a positive form of nature-based solutions[53,59,85], but rather also because citizens were engaged in decision-making through an electoral process, providing active communication and consensus exchange between the government and its citizens[86]. S-E system couplings in this example are about enhancing human–nature value shifts, and broadening the valuation process to become more inclusive, rather than exclusive. The process considered fundamental human well-being, ecosystem functionality, and a recognition of the importance of building human–nature connections and long-term relationships.

S-T couplings in rethinking growth, beyond this case, can also refer to leapfrogging with disruptive technologies that include short to long-term impacts within a blended finance, microfinance, green finance, and crypto-finance regulated framing to help leap ahead of the barriers around implementing more equitable approaches for how investment is delivered to communities. Core to rethinking growth here is the need to breakdown fundamentals of the economic and financial institutions that see profit-shareholder value as the end goal at the expense of communities, nature, and long-term sustainable futures for the subsequent generations. S-T couplings in this principle go further to include bringing disruptive decentralized energy systems, mobility, and autonomous ground and air transportation technologies that move beyond incremental, to fundamental shifts in decentralization, and which localize ownership of essential services and jobs[87]. For example, the Community Power Agency in Australia uses local, people-powered clean energy projects to bring social, environmental, and economic benefits to rural and remote communities[88].

Principle 2: Rethinking efficiency

Efficiency can be characterized in many ways, but in economics it is defined as Pareto efficiency, a desirable state, a resource allocation mechanism should achieve, in which no one can be made better off without making someone worse off[89]. Thus, efficiency is a welfare criterion for system design, be it a market or some other system. There is another, more intuitive and operational notion of efficiency, which concerns individual business profit maximization by means of increasing scale, specialization, and capital consolidation. Doubting that efficiency in the latter sense eventually leads to Pareto efficiency is deemed 'anti-market bias'[90], 'anti-profit beliefs'[91], or 'emporiophobia'[92]. However, this link is far from established, given the aggregate negative social and ecological consequences, such as environmental degradation, income inequality[93], and food insecurity[94]. We argue that we must rethink efficiency and our default endorsement of the pursuit of business efficiency. We follow others to challenge the dominant efficiency discourse on whether and how it serves normative goals of society and, instead, argue for a view and action that is inclusive of the wider stakeholders that are impacted by business operations. We thus argue for a, seemingly, radical shifting away from consumption-based monetary growth toward one that values and makes decisions based on non-exceedance of critical environmental thresholds[31,95]. Efficiency then cannot be viewed in strictly economic resource terms but should be on the basis of ecological limits, environmental health, and human well-being rather than the lowest common denominator of, e.g., widgets per hour per dollar invested. We advocate for effective social and ecological beneficial use rather than efficiency.

Rethinking efficiency involves recognizing that the short-term and segmented pursuit of efficiency can not only harm society but also hinder transformative changes. Rethinking efficiency could illuminate new path-dependencies that can constrain production, transport, energy, and manufacturing transitions[96] or assist the diversity of stakeholders within these sectors to visualize the advantages of transitions, thereby helping to reframe the economic, political, regulatory, and technical operational framing in which industries, cities, and communities operate[97]. For example, urban farming could be reconsidered as a more holistic regenerative economic and ecological enterprise within open space governance, in which elements of social inclusion, employment welfare and livelihoods, and ecological resilience are considered in unison. Efficiency and productivity are not sole determinants of this regenerative system, rather the emphasis is on the development of a greener and more inclusive city that can deliver multiple benefits.

An urban example is Bybi, a social enterprise that endeavors to achieve such rethinking efficiency goals through bees and honey production in Copenhagen, Denmark (http://bybi.dk/om_bybi/). Bybi is responsible for more than 250 bee colonies across the city of Copenhagen. ByBi rents beehives to public, private, and social organizations in the city of Copenhagen, and in return, they participate in events, tours, and courses facilitated by Bybi. The beehives are housed around the city and Bybi processes and sells the honey and by-products produced by these rented beehives. However, we do not highlight Bybi because it is alone transforming the local SETS or working with all rethinking principles. Rather, we include it here because this initiative is not fundamentally about production of honey, but about creating a multifunctional system that has social and ecological benefits, and works across sectors including companies, social projects, local citizens, cultural life, and institutions. Though a small local initiative, Bybi represents a seed of good Anthropocenes that can be examined for opportunities to scale, both as a specific initiative and as a way to rethink societies' focus on efficiency over inclusivity.

S-E couplings in this initiative emphasize the involvement of citizens in urban open space governance mediated by the central role insects and plants play to produce services and benefits. Stewardship in this case moves beyond the human as co-producer to encompass human and non-human interactions. Bybi actively employs unemployed people and those from vulnerable groups and provides training opportunities to those seeking new employment pathways. Low-income residents are provided a means of employment, which contributes to development of new skills and experiences necessary for future work. S-E couplings are showcased in how Bybi actively collaborates and engages with diverse stakeholders (residents, children, immigrants, unemployed, businesses, and government agencies) across the city to transport and distribute native and pollinator-friendly flower seeds for planting and pleasure. Here these actors collectively contribute to urban open space governance for people and insects and benefits are not focused on an efficiency model, but rather on shared human and non-human benefits.

Principle 3: Rethinking the state

To date, states have been unsuccessful in protecting the global ecological boundaries of the planet[95,98]. We argue that, despite calls for the dissolution of the state[10,99], and recognition of this failure, states do have capacity and obligation to assume a more significant role in generating positive futures while acknowledging their limitations. States are neither all-powerful nor redundant in solving global environmental problems. By rethinking the state, we mean a conception of governance in which the state is not seen only as reacting to market failures with regulation but is an actor that can support emerging multi-scale governance initiatives at global and local levels, inspire markets and people, give societal direction with goals and obligations toward the earth system[100], build capacity, mediate and resolve conflicts, and institutionalize best practices[101,102]. Therefore, transformative governance[103] is important for rethinking the state because it helps define issues of accountability, legitimacy, and transparency of decision-making and ultimately the political–market power relations that influence the implementation of new pathways[102,104]. In the 21st century, states must deal with a polycentric reality in which societal power is divided among a variety of public and private actors at all levels of governance ranging from local to global[105] working toward developing institutional flexibility, improved adaptive capacity, and ecosystem reflexivity via adaptive policies[106]. By rethinking the state, we seek to avoid the dual trap of negative externalities and societal instability associated with relying on markets alone, and the utopian picture in which powerful states have the political mandate and the power to force markets and people into submission with regulation[107]. By rethinking the state and harnessing its positive powers for good Anthropocenes, we also mean addressing how negative market externalities can be reduced and public participation and self-governance strengthened without losing the immense innovative potential that markets and people hold.

Despite compelling arguments illustrating structural barriers for states pushing transformative goals with significant economic and social trade-offs[95,98], there are also examples of states pushing transformative change despite such pushback. For example, the European Water Framework Directive (2000/60/EC) as an example of rethinking the state seeks to improve—and stop the deterioration of—the ecological condition of fresh surface and groundwaters as well as coastal waters within the European Union (EU). The legal obligations stemming from the directive for the EU member states, companies, and citizens are directly linked to ecological system boundaries and latest scientific knowledge. Similarly, impact-based regulatory strategies have been developed at the EU level in other sectors, most notably in climate change mitigation[108] and managing declining biodiversity[109]. Although such regulatory strategies can exemplify an advanced form of an environmental state rather than a green state respecting global ecological boundaries[98], it is notable that for instance in the water context, the Water Framework Directive is gaining transformative impact with ripple effects across most natural resource-intensive sectors with impact on water quality. For example, in 2019, the Supreme Administrative Court of Finland (SACF) declined an environmental permit from an estimated 1.4 billion euro industrial bioeconomy investment due to declining ecological water quality, despite major political controversy over the matter. The case exemplifies that legally binding goals can have a strong impact for sustainability, social and economic trade-offs notwithstanding. In this context, it is important to underscore that states are complex institutions in and by themselves with multiple levels, sectors, and actors[110], which have potential to facilitate overcoming structural barriers of transformation.

While the directive establishes a top-down planning and management structure for the EU waters, it also seeks to facilitate public and private collaboration, innovation, and tailored solutions for reaching the goals[111,112]. Here, the EU sets the overall, legally binding goals which are then implemented in state-level legislation, and ideally adapted to regional and local conditions in a collaborative process. While the role of such top-down instruments is controversial in societal transformations, research suggests that law can function as a crucial trigger for shifting governance onto a more sustainable pathway[113,114]. These shifts are far from linear and no top-down instrument—even one requiring contextualization and local-level involvement—can be expected to offer silver bullets in transforming governance. All such shifts are likely hindered by path dependencies in the governance cultures of institutions tasked with implementing change[111,112]. Top-down instruments can, however, plant the seeds toward shared visions of desirable transformations. In so doing, they perform a crucial societal task despite often slow and uneven progress, potentially providing a transformational change toward a steady-state economy that serves to deprioritize growth and market exploitation as state policy[95].

By considering S-E couplings in this case it is clear that ecological problems related to overuse and pollution of waters have historical roots and strong societal path-dependencies. Achieving good ecological status of waters cannot be solved in isolation of the social context that is producing them. Legitimate and effective governance solutions need buy-in from market and local actors, and also government-imposed direction as well as conflict mediation and resolution such as court proceedings. S-T couplings would also recognize the societal demand for, or the market imposition of, AI, IoT, and other smart solutions that are pushing rapid development in information technology. On a global level, servers and other information technology infrastructures are a major consumer of water. Water is needed to produce energy (either directly through hydropower, or indirectly through cooling nuclear, coal, or other operations), or to cool down servers. Competition over scarce resources escalates demand for conflict mediation and resolution related to water, and also demand for global planning and steering on the most ecologically suitable locations for running servers and other IT hubs sustainably.

Considering E-T couplings underlines the importance of new technological breakthroughs in monitoring of water status, water purification, water efficiency, flood management, and energy production that can help alleviate the ecological stress caused by human activity and help accumulate revenue from water. These technological breakthroughs alone are unlikely, however, to solve the overuse and pollution of waters in the long-term[115,116]. New technology creates room for new development which in turn creates new water-related challenges (e.g., a shift from water-intensive production of cotton to oil-based acrylic textiles causes release of vast quantities of microplastics to waters[117]). In order to foster a sustainable relationship between humans and water, a rethinking of the human–environment interface is required. States may need to impose limits for societally detrimental development with regulation, but the societal pathways toward this end should not be limited. Market and local actors need regulatory direction, and also room to innovate, adapt, and self-govern.

Principle 4: Rethinking the commons

The commons may concern ecological commons such as nature-based solutions[118], cultural commons such as music and arts[119], knowledge commons regarding social practices around knowledge[120], co-ownership and cooperatives[121], and also digital and hybrid commons referring to digital domains such as sharing platforms, bartering sites, cryptocurrencies, and open-source data platforms[122]. Rethinking the commons refers to changes in the way we understand, govern, and use physical, cultural, and intellectual commons to ensure their long-term availability to all members of a society.

For example, the recent surge in cities investing in nature-based solutions[27,59] showcase the pathways needed to rethink the natural resources and open space commons beyond the creation of green areas. Emphasis is placed on building trust in local government and the experimentation process, learning from social innovation, improved access, co-creation, and co-implementation[28,123]. The commons may serve as powerful opponents to the dominating capitalistic systems, which often counteract quests for more transformative changes toward good Anthropocene futures[17,18]. In this way, a commons-oriented approach promotes citizen-led innovation and participation[122].

Rethinking the commons includes the generation and qualitative improvement of new and existing public urban spaces. Whereas urban development often is focused on private development and the facilitation of car transportation, seeds of good Anthropocenes in urban development illustrates rethinking of urban spaces and an orientation toward more green, just, and healthy neighborhoods[124], also termed urban recalibration[125]. For example, the City of Barcelona has installed a series of superblocks, a grid of roads with interiors closed to motorized vehicles and above ground parking and gives preference to pedestrian traffic in the public space, combined with recreational areas, meeting places, and more greenery[126]. The interior of each superblock can be used by residential traffic, services, emergency vehicles, and loading/unloading vehicles under special circumstances[127].

E-T couplings in the Barcelona case could include making digital environmental data available for common use as it is increasingly provided from sensors, satellites, social media, and crowdsourcing. Equitable access to this data could provide both better information about challenges, and also enhanced capacities for co-creating innovative solution strategies sharing not only decision-making, but also the data and diverse forms of knowledge needed for decisions that can transform multiple domains of local SETS. Access to data and innovative use of technology, like other solutions, must be considered in contrast to social and ecological solutions and co-developed with residents to ensure that such urban development innovations are not co-opted by high private investments that prioritize economic returns relating to the establishment of sensor systems, and drive social abuses[128].

S-T couplings here involve re-emphasizing the role of public infrastructure as shared spaces, resources, and transportation services that can be provided for common use and more equitably. The digital commons can provide new possibilities for citizens to engage in the planning, design, and management of open spaces. In Barcelona, citizen science data is supplemented by data collected using smart sensors. Sensors are integrated into parking and transportation, to trash collection, air quality, and parkland irrigation. The data is fed into the 'Barcelona Digital City Platform'[129] which is available to citizens, private companies, and other interested parties, but the city and its people retain ultimate ownership, and decide what constitutes proper access and privacy[130]. Of course, tensions remain and need to be further examined, such as between ideals of the post-capitalism sharing economy or community economy practices, and the way in which the platform economy has developed with exploitative practices[128].

Principle 5: Rethinking justice

Rethinking justice in the Anthropocene is concerned with transforming the social, climate, economic, and political systems in ways that address disproportionate impacts and injustices. For example, climate change-driven extreme events are increasingly shown to have disproportionate impacts on the poor and marginalized, and there is concern regarding ethical issues around the unevenly allocated benefits of industrialization[131]. When considering risks from climate change impacts, this includes managing procedural, recognitional, and distributional justice issues associated with asymmetrical impact and skewed vulnerabilities[131,132]. Rethinking justice means also not only taking environmental and social justice movements further, but also advancing ecological justice, which evokes notions of reciprocity and care for humans and non-human entities, and so requires the exploration of new regulations and procedures for recognizing and managing for the rights of the non-human[132,133].

Fundamentally, rethinking justice means examining how, e.g., climate change impacts and climate resilience actions will affect the relationships between people and place[127], the range of knowledge and experiences of environmental change that impact everyday life for individuals and communities[133], as well as considering how these knowledges are integrated into the governance and management of the city[134]. Rethinking justice is also about building adaptive capacity to manage sudden, violent, and catastrophic weather events or slow, long-term destruction such as drought and wildfire through new forms of adaptive and more diverse representational governance[135].

For example, new forms of digital engagement and civic participation provide opportunities for recognizing the needs and rights of a diversity of interest groups[66]. In Dar es Salaam, Tanzania, East Africa's fastest growing city, university students and local residents have been engaged in a community-based mapping project called Ramani Huria (http://ramanihuria.org/) to create accurate maps of the most flood-prone areas of the city. Models predicting current and future flood risk are based on the data collected from the participatory mapping sessions digitized into OpenStreetMap and enhanced with GIS analysis and aerial photos from drones. This project drew on the knowledge of residents in an area of Dar es Salaam housing approximately 1.5 million people, the majority living in informal settlements and highlighted how environmental justice is fundamental to understanding climate risks. Results from this citizen science-based risk assessment processes revealed that while the majority of residents in flood-prone districts understand extreme flood risks, they are unable to move due to financial constraints, commuting time, or do not desire to move due to community and family ties.

Examining the S-E couplings in this case helps address elements of distributional and recognition justice in terms of who benefits from natural resources, and where. In a good Anthropocene, all living beings should have a right to access, occupy, and use urban space and exercise democratic control over the current and future development of the city. In Ramani Huria, residents' place-based knowledge has the potential to strengthen their rights and capability to live in their homes in the future. Residents can share information about flooding patterns and channels, risk of flooding, and flooding occurrence using participatory mapping tools, supporting climate resilience planning and empowering residents to better understand the issues, potential solutions, and methods of communicating climate risks to local authorities[136].

S-T couplings in Ramani Huria suggest that participatory approaches to digital geospatial technologies provide novel opportunities to investigate elements of procedural and distributional justice. Local knowledge can complement the data availability gap needed to model and predict future risk. This data is a useful source for adaptive community and multi-level governance decision-making about resilience to support residents' ability to stay in their homes. Next steps could support E-T couplings including multi-species monitoring and decision-making, giving voice and rights to local waterways.

Supporting transformation by connecting across principles

In 2020, society continues to deal with existential challenges generated by the social, political, and economic norms projected largely from the 20th century setting us on a potential path to deliver a dystopian future in which human society and ecological systems collapse. On the current path we can expect to confront the planetary limits of natural resources, not only to provide basic life-support services necessary for human survival, but also to adsorb the by-products generated by food and energy production, material transformations, with concomitant pollution of water, land, and air resources[63,74]. Indeed, considering climate change alone, even if all nations meet their carbon emission reduction targets under the Paris Agreement, remaining emissions put the world on climate change trajectory that may lead to a 3 °C or warmer world with dramatic social, ecological, and technological consequences few have been willing to contemplate.

We suggest that by re-evaluating and rethinking through a SETS conceptual approach some of the most important societal drivers of global environmental and social change, we can build pathways that allow for the radical transformations needed to move the human dominated earth system toward a shared urban future we all want. Dominant, conventional principles that need rethinking (among likely others) include: (1) growth: the economic growth paradigm (exemplified by GDP), with capitalism as the vehicle that is maintained as necessary for employment, upward mobility, and technical advance[74,75,137,138]; (2) efficiency: the efficiency of market systems and the assumption that businesses can efficiently and fully provide the goods and jobs necessary for a prosperous life within ecological limts[75]; (3) the state: the neoliberal narrative about the incompetence and inefficiency of the state and the assumption that the state should play a reactive rather than proactive role in environmental governance[22,11]; (4) the commons: that the commons deserve to be privatized or regulated by the state to avoid the potential for shared resources to be overexploited by individual users[105,107] and social–ecological systems frameworks, which provide for the regulation of the commons but often overlook how to facilitate and remove barriers to adaptive governance and self-organization to maintain resources[101,105,139]; and (5) justice: that humans and non-human species have unequal or even no rights to a clean and healthy environment[139].

Consideration of the five principles in isolation of one another will not drive transformations toward urban sustainability. Indeed, any single principle in itself is not necessarily novel, and has been well described in diverse literatures. The contribution we offer is to bring rethinking principles together as core needs that together must all be addressed to achieve the kinds of radical changes needed for fundamental societal transformations. The connections between the principles are foundational to any system change to ensure the integrity of S-T, S-E, and E-S couplings during the implementation of disruptive innovations and to avoid siloing of innovative solutions. Intermediaries, also termed intermediary actors[139] or knowledge brokers[140], support accelerating transitions toward more sustainable pathways by removing or reducing blockages, pre-empting unintended consequences of change dynamics, and thus connecting different components and domains of the system[141] in what we refer to as fostering the 'connective tissues' between SETS strands.

Strong connective tissues including strong causal interactions between system components are also necessary for positive tipping points in the form of 'domino dynamics' or a 'tipping cascade' where one system causes the tipping of another, or to ensure deliberate interventions into a given principle can take the whole system down an alternative path[35]. Strong tissues can also provide resilience to negative stressors. Following Elmqvist et al. (2019)[28], we propose that these tissues enable a system to maintain function in the eve and aftermath of a disturbance.

Recent examples of these tissues include the sudden shift to virtual care in Australia in 2020. While in part driven by COVID-19, this shift also reflects a connection between a rethinking of efficiency, the state, the commons, and justice. On March 13, 2020 the Australian Government added new telehealth items to the Medicare Benefits Schedule enabling health-care providers to offer both telephone and video consultations. This scheme was extended to all Australian patients on March 30. Before then, Australians inside major cities did not have access to these services. With a system change, the total number of consultations rose significantly, from 10.8 million in February to 12.9 million in April, 2020. The telehealth switch also prompted an overnight shift in the way health care is delivered in Australia[142]. The government made sudden changes to legislation and regulation, and finance and support programs to enable online treatment (e.g., rethinking the state). Justice principles were also re-thought concurrently with the provision of new apps and technologies for health delivery. To avoid many of the issues associated with patient isolation, AUS$10 million was assigned to the existing community visitors' scheme and to train volunteer visitors to combat social isolation caused by COVID-19 (e.g., rethinking justice). New apps were developed to enable volunteer visitors to connect with older people both online and by phone[143]. We may expect trade-offs to emerge associated with the rapid delivery of these online support systems, including the increased inequality due to people's different abilities to afford smartphones or computers, or difficulties to consult over the phone. Time will tell whether this initiative is transformative over the longer term, but it serves as an example that shifts can happen across rethinking principles, and even quickly[144–146].

We provide the example to illustrate how strong connective tissues between the principles are needed, and that all five rethinking principles will need to be operationalized together for fundamental SETS transformations. The SETS framework, combined with connections across the rethinking principles, can help to identify potential trade-offs and ways to address them while aiming for transformative change. In this way, the five rethinking principles 'pull' the evolution of the coupled SETS strands toward more transformative pathways creating the conditions for good Anthropocene futures, while the connective tissue between the SETS strands can enable a close coupling and a coordinated realignment of societal activities, goals, and opportunities (Fig. 3).

Radical rethinking for good Anthropocenes

We assert that society needs to not only rethink the conventional principles and their underlying drivers that define the status quo and underpin the current trajectories that put us on pathways toward dystopian Anthropocene futures, but also the connections among them to ensure transformative change. In our SETS framing, good Anthropocenes are ones where the steering arms of society including embedded financial, market, legal, political, and governance systems are realigned and coordinated through connective tissues so as to support multi-functionality. The tissues enable connectivity among social, ecological, and technological domains of SETS. We propose that radical rethinking along the five fundamental principles, combined with governance systems to strengthen the connective tissues among them, are paramount to enabling critical transformations toward good Anthropocenes. We have provided some examples of early 'seeds' of those rethinking principles in action that provide a starting point, though these are neither perfect examples nor address all principles or all SETS couplings (explore more seeds further at goodanthropocenes.net). There is still considerable need for advancing sustainability research for transformation. We suggest five key actions for research scientists to effectively contribute to this advancement.

1. Take a systems approach to all sustainability research, taking into account the couplings, and interplay between the social–technological (S-T), social–ecological (S-E), and ecological–technological (E-T) systems. The connective tissues between transformation principles are crucial to ensure the operational integrity of the couplings.
2. Go beyond interdisciplinary research to learn new scientific languages, collaborate with other scientific disciplines, and train toward transdisciplinarity throughout the primary, secondary, and tertiary education systems;
3. Co-produce and co-design sustainability research with communities to bring diverse knowledges to research and practice that is grounded at the scales where challenges are experienced;
4. Recognize and take actions that can push your research to question the status quo with and across disciplines, with the five principles described here;
5. Deliberately create positive tipping points in urban and regional systems—strategically identify actions for creating and strengthening tissues between the principles of rethinking growth, efficiency, the state, the commons, and justice.

We encourage further studies to identify similar SETS couplings, to put forward additional principles that must be re-thought, and to support their mainstreaming together to help initiate and foster the radical transformations toward a good Anthropocene urgently needed.

DATA AVAILABILITY

The data used for plots in Fig. 1 are available from the corresponding author upon reasonable request.

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REFERENCES

1. Jeanson, A. L. et al. Twenty actions for a "good Anthropocene"—perspectives from early-career conservation professionals. *Environ. Rev.* **28**, 99–108 (2019).
2. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. *Summary for Policymakers Of The Global Assessment*. Report on Biodiversity and Ecosystem Services. https://doi.org/10.5281/ZENODO.3553579 (IPBES, 2019).
3. Intergovernmental Panel on Climate Change. *IPCC Fifth Assessment Report.* Climate Change 2014, Synthesis Report. http://ar5-syr.ipcc.ch/ (IPCC, 2014).
4. Kok, K., Pedde, S., Gramberger, M., Harrison, P. A. & Holman, I. P. New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. *Reg. Environ. Change* **19**, 643–654 (2019).
5. Ripple, W. J., Wolf, C., Newsome, T. M., Barnard, P. & Moomaw, W. R. World scientists' warning of a climate emergency. *BioScience* **70**, 8–12 (2020).
6. Lewis, S. L. & Maslin, M. A. Defining the Anthropocene. *Nature* **519**, 171–180 (2015).
7. Seddon, N. et al. Biodiversity in the Anthropocene: prospects and policy. *Proc. R. Soc. B* **283**, 20162094 (2016).
8. Steffen, W. et al. Trajectories of the earth system in the Anthropocene. *Proc. Natl Acad. Sci.USA* **115**, 8252–8259 (2018).
9. Ellis, E. *Anthropocene: A Very Short Introduction* (Oxford University Press, 2018).
10. Reich, R. B. *The System: Who Rigged It, How We Fix It*. (Picador, 2020).

11. Raworth, K. *Doughnut Economics: Seven Ways to Think Like a 21st-century Economist* (Chelsea Green Publishing, 2017).
12. Richardson, K. et al. Climate tipping points—too risky to bet against. *Nature* **575**, 592–595 (2019).
13. Temper, L., Walter, M., Rodriguez, I., Kothari, A. & Turhan, E. A perspective on radical transformations to sustainability: resistances, movements and alternatives. *Sustain. Sci.* **13**, 747–764 (2018).
14. Burch, S., Shaw, A., Dale, A. & Robinson, J. Triggering transformative change: a development path approach to climate change response in communities. *Climate Policy* **14**, 467–487 (2014).
15. C40. *The Global Green New Deal*. https://www.c40.org/other/the-global-green-new-deal (2019).
16. Ekblom, J. *Factbox: What is von der Leyen's European Green Deal*? (Reuters, 2019).
17. Raudsepp-Hearne, C. et al. Seeds of good Anthropocenes: developing sustainability scenarios for Northern Europe.*Sustain. Sci.* **15**, 605–617 (2020).
18. Bennett, E. M. et al. Bright spots: seeds of a good Anthropocene. *Front. Ecol. Environ.* **14**, 441–448 (2016).
19. Elmqvist, T. et al. Benefits of restoring ecosystem services in urban areas. *Curr. Opin. Environ. Sustain.* **14**, 101–108 (2015).
20. Reich, R. B. *The Common Good* (Knopf, 2018).
21. Sen, A. Totally radical: from transformative research to transformative innovation. *Sci. Publ. Policy* **41**, 344–358 (2014).
22. Pirgmaier, E. & Steinberger, J. K. Roots, riots, and radical change—a road less travelled for ecological economics. *Sustainability* **11**, 2001 (2019).
23. Hamstead, Z. A. et al. (eds.) A vision for resilient urban futures. In *Resilient Urban Futures*. https://doi.org/10.1007/978-3-030-63131-4 (Springer International Publishing, 2021).
24. Gurara, D., Klyuev, V., Mwase, N. & Presbitero, A. F. Trends and challenges in infrastructure investment in developing countries. *Rev. Int. Dev. Pol.* 10, https://journals.openedition.org/poldev/2802 (2018).
25. Parnell, S., Elmqvist, T., McPhearson, P. T., Nagendra, H. & Sörlin, S. Introduction: Situating knowledge and action for an urban planet. In *Urban Planet: Knowledge Towards Sustainable Cities* (eds. Elmqvist, T. et al.). https://doi.org/10.1017/9781316647554.002 (Cambridge University Press, 2018).
26. Seto, K. C., Güneralp, B. & Hutyra, L. R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl Acad. Sci. USA* **109**, 16083–16088 (2012).
27. Bai, X. et al. Defining and advancing a systems approach for sustainable cities. *Curr. Opin. Environ. Sustain.* **23**, 69–78 (2016).
28. Elmqvist, T. et al. Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* **2**, 267–273 (2019).
29. United Nations, Department of Economic and Social Affairs, Population Division. *World Urbanization Prospects*: *The 2018 Revision* (ST/ESA/SER.A/420) (UN, 2019).
30. McPhearson, T., Iwaniec, D. M. & Bai, X. Positive visions for guiding urban transformations toward sustainable futures. *Curr. Opin. Environ. Sustain.* **22**, 33–40 (2017).
31. Büchs, M. & Koch, M. Challenges for the degrowth transition: the debate about wellbeing. *Futures* **105**, 155–165 (2019).
32. McPhillips, L. E. et al. Defining extreme events: a cross-disciplinary review. *Earth's Future* **6**, 441–455 (2018).
33. Mechler, R., Bouwer, L. M., Schinko, T., Surminski, S. & Linnerooth-Bayer, J. *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* (Springer, 2018).
34. Hamilton, C. The theodicy of the "Good Anthropocene". *Environ. Hum.* **7**, 233–238 (2016).
35. Nolan, C. et al. Past and future global transformation of terrestrial ecosystems under climate change. *Science* **361**, 920–923 (2018).
36. Lenton, T. M. Tipping positive change. *Philos. Trans. R. Soc. B* **375**, 20190123 (2020).
37. Hamilton, C. The Anthropocene as rupture. *Anthropocene Rev.* **3**, 93–106 (2016).
38. Meadows, D. H. *Thinking in Systems: A Primer* (Earthscan, 2009).
39. Lam, D. P. M. et al. Scaling the impact of sustainability initiatives: a typology of amplification processes. *Urban Transform.* **2**, 3 (2020).
40. Mangnus, A. et al. New pathways for governing food system transformations: a pluralistic practice-based futures approach using visioning, back-casting, and serious gaming. *Ecol. Soc.* 24, https://doi.org/10.5751/ES-11014-240402 (2019).
41. Pereira, L. M. et al. Seeds of the future in the present: exploring pathways for navigating towards "Good" Anthropocenes. In *Urban Planet: Knowledge Towards Sustainable Cities* (eds. Griffith, C. et al.) 327–350. https://doi.org/10.1017/9781316647554.018 (Cambridge University Press, 2018).
42. Pereira, L. et al. Seeding change by visioning good anthropocenes. Solutions Journal. https://www.thesolutionsjournal.com/article/seeding-change-visioning-good-anthropocenes/. (2019).
43. Ives, C. D., Freeth, R. & Fischer, J. Inside-out sustainability: the neglect of inner worlds. *Ambio* **49**, 208–217 (2020).
44. Berkes, F. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change* (Cambridge University Press, 2008).
45. Liu, J. et al. Complexity of coupled human and natural systems. *Science* **317**, 1513–1516 (2007).
46. Pan, H. et al. Using comparative socio-ecological modeling to support Climate Action Planning (CAP). *J. Clean. Prod.* **232**, 30–42 (2019).
47. Edmondson, D. L., Kern, F. & Rogge, K. S. The co-evolution of policy mixes and socio-technical systems: towards a conceptual framework of policy mix feedback in sustainability transitions. *Res. Policy* **48**, 103555 (2019).
48. Grimm, N. B., Cook, E. M., Hale, R. L. & Iwaniec, D. M. A broader framing of ecosystem services in cities: benefits and challenges of built, natural, or hybrid system function https://doi.org/10.4324/9781315849256.ch14 (Routledge Handbooks Online, 2015).
49. McPhearson, T. et al. Advancing urban ecology toward a science of cities. *BioScience* **66**, 198–212 (2016).
50. Markolf, S. A. et al. Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future* **6**, 1638–1659 (2018).
51. Miremadi, T. Coupling multilevel perspective with causal layered analysis on non-reflexive societies the case of socio-technical system of car fuel in Iran. *Technol. Forecast.Soc. Change* **155**, 120029 (2020).
52. Bennett, N. J., Blythe, J., Tyler, S. & Ban, N. C. Communities and change in the Anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. *Reg. Environ. Change* **16**, 907–926 (2016).
53. McPhearson, T. et al. A social-ecological-technological systems framework for urban ecosystem services. One Earth (In revision).
54. Zhou, W., Pickett, S. & McPhearson, T. Conceptual frameworks facilitate integration for transdisciplinary urban science. npj Urban Sustainability (2021).
55. Grabowski, Z. J. et al. Infrastructures as socio-eco-technical systems: five considerations for interdisciplinary dialogue. *J. Infrastruct. Syst.* **23**, 02517002 (2017).
56. Ahlborg, H., Ruiz-Mercado, I., Molander, S. & Masera, O. Bringing technology into social-ecological systems research—motivations for a socio-technical-ecological systems approach. *Sustainability* **11**, 2009 (2019).
57. Gulsrud, N. M. et al. 'Rage against the machine'? The opportunities and risks concerning the automation of urban green infrastructure. *Landsc. Urban Plan.* **180**, 85–92 (2018).
58. Depietri, Y. & McPhearson, T. Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction. In *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (eds. Kabisch, N., Korn, H., Stadler, J. & Bonn, A.) 91–109 https://doi.org/10.1007/978-3-319-56091-5_6 (Springer International Publishing, 2017).
59. Keeler et al. Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustain.* **2**, 29–38 (2019).
60. Andersson, E. et al. Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. *Ambio* **43**, 445–453 (2014).
61. Ilieva, R. T. & McPhearson, T. Social-media data for urban sustainability. *Nat. Sustain.* **1**, 553–565 (2018).
62. Ortiz, L. E. et al. High-resolution projections of extreme heat in New York City. *Int. J. Climatol.* **39**, 4721–4735 (2019).
63. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
64. Sachs, J. D. et al. Six transformations to achieve the sustainable development goals. *Nat. Sustain.* **2**, 805–814 (2019).
65. United Nations. *Transforming Our World: the 2030 Agenda for Sustainable Development*. https://sustainabledevelopment.un.org/post2015/transformingourworld (UN, 2015).
66. Fritz, S. et al. Citizen science and the United Nations Sustainable Development Goals. *Nat. Sustain.* **2**, 922–930 (2019).
67. Buijs, A. et al. Active citizenship for urban green infrastructure: fostering the diversity and dynamics of citizen contributions through mosaic governance. *Curr. Opin. Environ. Sustain.* **22**, 1–6 (2016).
68. Venables, A. J. Incorporating wider economic impacts within cost–benefit appraisal. In *Quantifying the Socio-economic Benefits of Transport*, 109–127 https://doi.org/10.1787/9789282108093-6-en (OECD, 2017).
69. OECD, UN Environment & The World Bank. *Financing Climate Futures: Rethinking Infrastructure* (OECD, 2018).
70. de Jesus, A., Antunes, P., Santos, R. & Mendonça, S. Eco-innovation pathways to a circular economy: envisioning priorities through a Delphi approach. *J. Clean. Prod.* **228**, 1494–1513 (2019).
71. U.N. Environment Programme. *Inclusive Wealth Report 2018*. http://www.unep.org/resources/report/inclusive-wealth-report-2018 (UN, 2018).
72. Himes, A. & Muraca, B. Relational values: the key to pluralistic valuation of ecosystem services.*Curr. Opin. Environ. Sustain.* **35**, 1–7 (2018).

73. Weiss, M. & Cattaneo, C. Degrowth—taking stock and reviewing an emerging academic paradigm. *Ecol. Econ.* **137**, 220–230 (2017).
74. Cosme, I., Santos, R. & O'Neill, D. W. Assessing the degrowth discourse: a review and analysis of academic degrowth policy proposals. *J. Clea. Prod.* **149**, 321–334 (2017).
75. Perkins, P. E. Climate justice, commons, and degrowth. *Ecol. Econ.* **160**, 183–190 (2019).
76. Hankammer, S. & Kleer, R. Degrowth and collaborative value creation: Reflections on concepts and technologies. *J. Clean. Prod.* **197**, 1711–1718 (2018).
77. Fuso Nerini, F. et al. Connecting climate action with other sustainable development goals. *Nat. Sustain.* **2**, 674–680 (2019).
78. Ershad Sarabi, S., Han, Q., Romme, A.G.L., de Vries, B. & Wendling, L. Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: a review.*Resources* **8**, 121 (2019).
79. Daly, H. E. *Steady-State Economics*, 2nd edn. (Island Press, 1991).
80. Meadows, D. H., Meadows, D. L., Randers, J. & Behrens III, W. W. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (Universe Books, 1974).
81. O'Neill, D. W., Fanning, A. L., Lamb, W. F. & Steinberger, J. K. A good life for all within planetary boundaries. *Nat. Sustain.* **1**, 88–95 (2018).
82. Schuttler, S. G., Sorensen, R. C., Jordan, C., Cooper, C. & Shwartz, A. Bridging the nature gap: can citizen science reverse the extinction of experience? *Front. Ecol. Environ.* **16**, 405–411 (2018).
83. Coles, N. A. et al. *Analysis of the Business Case for the Application of the Nature Based Solutions* (ThinkNature, 2019).
84. Landscape Architecture Foundation. *Cheonggyecheon Stream Restoration Project*. Landscape Performance Series https://www.landscapeperformance.org/case-study-briefs/cheonggyecheon-stream-restoration (2011).
85. Frantzeskaki, N. et al. Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making.*BioScience* **69**, 455–466 (2019).
86. Amirtahmasebi, R., Orloff, M., Wahba, S. & Altman, A. *Regenerating Urban Land: A Practitioner's Guide to Leveraging Private Investment* (World Bank Publications, 2016).
87. Rifkin, J. *The Third Industrial Revolution: How Lateral Power Is Transforming Energy, the Economy, and the World*. (St. Martin's Griffin, 2013).
88. Community Power Agency. *Driving A Faster & Fairer Transition To Clean Energy*. Community Power Agency https://cpagency.org.au/. Accessed 01 Dec 2020.
89. Varian, H. R. *Intermediate Microeconomics: A Modern Approach*. (W. W. Norton & Company, 2014).
90. Caplan, B. *The Myth of the Rational Voter: Why Democracies Choose Bad Policies -* New Edition (Princeton University Press, 2008).
91. Bhattacharjee, A., Dana, J. & Baron, J. Anti-profit beliefs: how people neglect the societal benefits of profit. *J. Personal. Soc. Psychol.* **113**, 671–696 (2017).
92. Rubin, P. H. Emporiophobia (fear of markets): cooperation or competition? *South. Econ. J.* **80**, 875–889 (2014).
93. Ota, T. Economic growth, income inequality and environment: assessing the applicability of the Kuznets hypotheses to Asia. *Palgrave Commun.* **3**, 1–23 (2017).
94. Schramski, J. R., Woodson, C. B., Steck, G., Munn, D. & Brown, J. H. Declining country-level food self-sufficiency suggests future food insecurities. *Biophys. Econ. Resour. Qual.* **4**, 12 (2019).
95. Koch, M. The state in the transformation to a sustainable postgrowth economy. *Environ. Politics* **29**, 115–133 (2020).
96. Cainelli, G., D'Amato, A. & Mazzanti, M. *Resource Efficiency, Environmental Policy and Eco-Innovations for a Circular Economy: Evidence from EU Firms*. https://papers.ssrn.com/abstract=3070397 (2017).
97. Vadén, T. et al. To continue to burn something? Technological, economic and political path dependencies in district heating in Helsinki, Finland. *Energy Res. Soc. Sci.* **58**, 101270 (2019).
98. Hausknost, D. The environmental state and the glass ceiling of transformation. *Environ. Politics* **29**, 17–37 (2020).
99. Schifeling, T. Agents of neoliberal globalization: corporate networks, state structures, and trade policy.*Contemp. Sociol.* **47**, 450–452 (2018).
100. Burdon, P.D. Obligations in the Anthropocene.*Law Critique* **31**, 309–328 (2020).
101. Cosens, B. et al. The role of law in adaptive governance.*Ecol. Soc.* **22**, 30 (2017).
102. Chaffin, B. C. et al. Transformative environmental governance. *Annu. Rev. Environ. Res.* **41**, 399–423 (2016).
103. Hölscher, K. & Frantzeskaki, N. (eds.) *Transformative Climate Governance: A Capacities Perspective to Systematise, Evaluate and Guide Climate Action*. https://doi.org/10.1007/978-3-030-49040-9 (Palgrave Macmillan, 2020).
104. Craig, R. et al. Balancing stability and flexibility in adaptive governance: an analysis of tools available in U.S. environmental law.*Ecol. Soc.* **22**, 3 (2017).
105. Dietz, T., Ostrom, E. & Stern, P. C. The struggle to govern the commons. *Science* **302**, 1907–1912 (2003).
106. Dryzek, J. S. Institutions for the Anthropocene: governance in a changing earth system. *Br. J. Political Sci.* **46**, 937–956 (2016).
107. Hardin, G. The tragedy of the commons. *Science* **162**, 1243–1248 (1968).
108. European Commission. EU climate action and the European Green Deal. *Climate Action - European Commission.* https://ec.europa.eu/clima/policies/eu-climate-action_en (2019).
109. European Commission. *EU Biodiversity Strategy for 2030*. https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm (2019).
110. Camacho, A. & Glicksman, R. *Reorganizing Government: A Functional and Dimensional Framework* (NYU Press, 2019).
111. Jager, N. W. et al. Transforming European water governance? Participation and river basin management under the EU Water Framework Directive in 13 member states. *Water* **8**, 156 (2016).
112. Voulvoulis, N., Arpon, K. D. & Giakoumis, T. The EU Water Framework Directive: from great expectations to problems with implementation. *Sci. Total Environ.* **575**, 358–366 (2017).
113. Cosens, B. & Gunderson, L. (eds.) *Practical Panarchy for Adaptive Water Governance: Linking Law to Social-Ecological Resilience*. https://doi.org/10.1007/978-3-319-72472-0 (Springer International Publishing, 2018).
114. Vörösmarty, C. J., Hoekstra, A. Y., Park, S. E. & Conway, D. What scale for water governance? *Science* **349**, 478–478 (2015).
115. Pahl-Wostl, C. *Water Governance in the Face of Global Change: From Understanding to Transformation*. https://doi.org/10.1007/978-3-319-21855-7 (Springer International Publishing, 2015).
116. Grunwald, A. Diverging pathways to overcoming the environmental crisis: a critique of eco-modernism from a technology assessment perspective. *J. Clean. Prod.* **197**, 1854–1862 (2018).
117. De Falco, F., Di Pace, E., Cocca, M. & Avella, M. The contribution of washing processes of synthetic clothes to microplastic pollution. *Scientific Rep.* **9**, 1–11 (2019).
118. Raymond, C. M. et al. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **77**, 15–24 (2017).
119. Marrelli, M. & Fiorentino, P. Cultural commons and local art markets: zero-miles contemporary art in Naples.*City, Culture Soc.* **7**, 117–122 (2016).
120. Hess, C. & Ostrom, E. *Understanding Knowledge as a Commons: From Theory to Practice* (MIT Press, 2007).
121. Wierling, A. et al. Statistical evidence on the role of energy cooperatives for the energy transition in European Countries. *Sustainability* **10**, 3339 (2018).
122. Niaros, V., Kostakis, V. & Drechsler, W. Making (in) the smart city: the emergence of makerspaces. *Telemat. Inform.* **34**, 1143–1152 (2017).
123. Frantzeskaki, N. & Kabisch, N. Designing a knowledge co-production operating space for urban environmental governance: lessons from Rotterdam, Netherlands and Berlin, Germany. *Environ. Sci. Policy* **62**, 90–98 (2016).
124. Kraas, F. et al. *Humanity on the Move: Unlocking the Transformative Power of Cities* (WBGU - German Advisory Council on Global Change, 2016).
125. Cervero, R., Guerra, E. & Stefan, A. I. *Beyond Mobility: Planning Cities for People and Places*. https://doi.org/10.5822/978-1-61091-835-0 (Island Press/Center for Resource Economics, 2017).
126. Barcelona City Council. *The new Sant Antoni Superblock Regains 5,000 Square Metres for use by Local Residents* (Barcelona City Council, 2018).
127. Agencia de Ecología Urbana de Barcelona. *SUPERBLOCKS* (Agencia de Ecología Urbana de Barcelona, 2012).
128. Gulsrud, N. M., Hertzog, K. & Shears, I. Innovative urban forestry governance in Melbourne?: Investigating "green placemaking" as a nature-based solution. *Environ. Res.* **161**, 158–167 (2018).
129. City of Barcelona. *Barcelona Digital City*. https://ajuntament.barcelona.cat/digital/en (2019).
130. Urban Hub. *Smart city 3.0: Ask Barcelona About the Next Generation of Smart Cities*. http://www.urban-hub.com/cities/smart-city-3-0-ask-barcelona-about-the-next-generation-of-smart-cities/ (2018).
131. Robinson, M. & Shine, T. Achieving a climate justice pathway to 1.5 °C. *Nat. Clim. Change* **8**, 564–569 (2018).
132. Schlosberg, D. Disruption, community, and resilient governance: environmental justice in the Anthropocene. In *The Commons in a Glocal World: Global Connections and Local Responses*. https://doi.org/10.4324/9781351050982 (Routledge, 2019)
133. Haraway, D. Anthropocene, capitalocene, plantationocene, chthulucene: making kin. *Environ. Hum.* **6**, 159–165 (2015).
134. Haller, T., Belsky, J. M. & Rist, S. The constitutionality approach: conditions, opportunities, and challenges for bottom-up institution building. *Hum. Ecol.* **46**, 1–2 (2018).
135. Pickering, J. Ecological reflexivity: characterising an elusive virtue for governance in the Anthropocene. *Environ. Politics* **28**, 1145–1166 (2019).

136. Mearns, R. & Norton, A. *The Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World*. https://doi.org/10.1596/978-0-8213-7887-8 (The World Bank, 2009).
137. Meadows, D. H., Randers, J. & Meadows, D. L. *Limits to Growth: The 30-Year Update* (Chelsea Green Publishing, 2004).
138. Scheidel, A. & Schaffartzik, A. A socio-metabolic perspective on environmental justice and degrowth movements. *Ecol. Econ.* **161**, 330–333 (2019).
139. Jasanoff, S. *The Fifth Branch: Science Advisers as Policymakers* (Harvard University Press, 1998).
140. Pielke, R. A. *The Honest Broker: Making Sense of Science in Policy and Politics* (Cambridge University Press, 2007).
141. Kivimaa, P., Boon, W., Hyysalo, S. & Klerkx, L. Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda. *Res. Policy* **48**, 1062–1075 (2019).
142. Smith, A., Snoswell, C. & Caffery, L. *Telehealth in Lockdown Meant 7 Million Fewer Chances to Transmit the Coronavirus*. The Conversation http://theconversation.com/telehealth-in-lockdown-meant-7-million-fewer-chances-to-transmit-the-coronavirus-141041 (2020).
143. Fisk, M., Livingstone, A. & Pit, S. W. Telehealth in the context of COVID-19: changing perspectives in Australia, the United Kingdom, and the United States. *J. Med. Internet Res.* **22**, e19264 (2020).
144. Keys, P. W. et al. Anthropocene risk. *Nat. Sustain.* **2**, 667–673 (2019).
145. Geels, D. I. F. W. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technol. Anal. Strategic Manag.* **17**, 445–476 (2005).
146. Berkes, F. Environmental governance for the Anthropocene? Social-ecological systems, resilience, and collaborative learning. *Sustainability* **9**, 1232 (2017).
147. Grubler, A. et al. Energy Primer. In Global Energy Assessment: Toward a Sustainable Future (ed. Global Energy Assessment Writing Team) 99–150 https://doi.org/10.1017/CBO9780511793677.007 (Cambridge University Press, 2012).
148. Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* **2**, (2015).

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