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Life on New Earth: biodiversity change and humanity in a novel future

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Accounting for ecological novelty, gains and past human experiences through social–ecological–technological systems (SETS) can help society navigate accelerating global biodiversity change. Popular narratives stress escalating loss of species and ecosystems, and the potential collapse of the benefits they provide to people. In the public sphere, this can present the spectre of an uninhabitable Earth and the extinction of the human species. Research suggests that these crisis narratives can raise awareness, but are counterproductive in stimulating mitigating or adaptive action. They also omit evidence of biodiversity gains and ongoing adaptation alongside losses. Archaeological evidence also highlights the human ability to take advantage of and thrive under an extremely wide range of changing and challenging ecological conditions and the provisioning opportunities these provide. This perspective provides an evidenced counterargument to claims of civilizational collapse amid environmental change. Projections show that rather than universal ecological decline, a cosmopolitan biosphere of losses and gains will probably emerge. Distilled, these insights provoke a new research agenda, centred on how we measure, frame and imagine alternative futures so that we can systematically explore pathways and scenarios for a just and thriving humanity on a climatically and ecologically transforming Earth.

This article is part of the theme issue 'The biosphere in the Anthropocene'.

1. Introduction

For every argument that ecosystem services are declining, that we face a sixth mass extinction, or that catastrophic tipping points are around the corner, or even that humanity is doomed, there are counter arguments. Most researchers and commentators nevertheless agree that the rate of biodiversity change is extremely fast at present, and has accelerated over the past century. Rapid rates of change imply a combination of losses and gains, affecting biodiversity, humanity and technology, as well as the unfolding, stochastic interactions between them. Important, but often overlooked in this discourse, are the

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relative magnitudes and locations of the ecological losses and gains, the likelihoods of future losses and gains and how they are framed. Changes do not inevitably follow a trajectory of loss at the expense of gain, and not all biodiversity losses or gains can be regarded as distinctly negative or positive. Thus, what matters for people is how biodiversity changes intersect with the wider social–ecological–technological systems (SETS) in which they are situated.

Periods of mass extinction [1], climatic shifts, biotic changes [2] and other transitions have occurred at seasonal, millennial and geological timescales often beyond the typical ken of most people across human history. Since the appearance of *Homo sapiens* in Africa approximately 300 ka, successive waves [3] of the species migrated and eventually settled and developed advanced cultures. Civilizations adapted, at varying population densities, to a wide range of biological conditions, from hyper-arid deserts, tropical and temperate forests, grasslands and high mountains to the arctic tundra and through periods of glaciation and warmer interglacials.

The link between biodiversity and food security is well established, in that biodiversity helps to regulate nutrient and water cycles, promotes soil fertility, crop pollination and diversity (thus dietary nutrition) and livelihoods [4–6], linked historically and globally by trade [7]. Human societies, past and present, developed technologies and food production systems to manage this biodiversity to meet their needs. Although some species disappeared [8], in multiple locations across the Earth's surface, human settlement, landscape modification and ecological management had net positive effects on some aspects of measured biodiversity over yearly to multi-millennial timescales [8–12]. At the same time, megafaunal extinctions and associated ecological functions are also strongly correlated with human expansion and overexploitation, indicating the significant and cascading impacts that these activities can also have [13].

Humans thus have a long evolutionary, prehistoric, historic and contemporary track record of learning to live, by sourcing essentials like food, in the harshest environments on the planet, beginning long before the industrial production of goods and energy, global trade, information technology and telecommunications heralded 'The Great Acceleration' [14]. Today, in addition to social–ecological adaptation and cognitive agility that facilitated millennia of human adaptation, society has access to technology that is sophisticated enough to maintain habitable conditions in submarine and orbital environments. The 'Space Age' saw the construction of space stations—such as Mir, Skylab, Tiangong and the International Space Station—that have been able to sustain human habitation, while ongoing efforts may do so for lunar and Martian habitats, possibly in the coming decades.

Despite this trajectory of constant adaptation to comfortable and austere environments, ranging from low to abundant biodiversity, the discourse of social–ecological futures remains persistently dystopian, exacerbated by popular writing [15–18] and ongoing scientific documentation of ecological changes and losses [19–22]. Some scholars suggest we are entering Earth's sixth mass extinction [23–25], a position based on the elevated extinction rate in comparison with estimated base rates from the fossil record and high projected future rates [25]. Some such studies conclude with polemic statements such as 'our destruction of the global biological richness on which we utterly depend represents an unprecedented threat to the existence of civilization that could even threaten the persistence of humanity' [26].

However, interspersed with this outlook are scientifically informed movements to provide alternative narratives and address environmental change centred on scales ranging from placed-based initiatives [27] to multilateral global frameworks and goal-setting for climate, biodiversity and development. These efforts include the Sustainable Development Goals (SDGs) [28], Paris Agreement [29] and the Montreal-Kunming Biodiversity Framework [30]. Yet such institutional goal setting in response to loss-focused narratives and the science of peril has so far failed to produce effective mitigation and adaptation strategies at scale and is mired in complex politics. The Earth continues to heat rapidly and change ecologically. But does this mean doom for humanity, or will alternative perspectives reveal something else?

We argue that current catastrophic outlooks preclude a more nuanced view of gains amid the losses, and the opportunities these might reveal for the forging of viable pathways within novel ecosystems and climates. Our paper explores the relationship between losses and gains, making the case that it can be helpful to frame future Earth as ecologically different, not universally degraded. We build a case by discussing how framing human habitability as a question of social–ecological–technological systems (SETS) can help us conceptualize habitable and just Earth futures on a biogeographically and climatically changed and dynamic planet. We integrate SETS into examples from the archaeological record to show how past societies harnessed different capacities to adapt to a wide range of environments. We then discuss SETS in the context of justice and how we might frame the present and future adaptations to living on a rapidly changing Earth. The aim of this perspective is not to refute or minimize the evidence that major species declines are occurring or that many human communities and regions are, or will, experience major, acute and inequitable impacts from ongoing environmental change, all of which we agree require urgent attention. Rather, our aim is to stress the need to *also* look beyond these impacts to consider longer-term and global visions for viable futures on an ecologically transformed Earth and to present a new research agenda to outline such futures [31].

We set out our argument first in §2 with a review of loss and gain in biodiversity science and (in §3) a discussion of tipping points and boundaries, then (§4) an explanation and application of SETS to examples from the archaeological literature, and we close (§5)with a discussion of the implications.

2. Biodiversity losses are uneven and there are gains

Redford and Sanjayan, in a provocation written more than 20 years ago, lamented that the crisis narrative of loss and extinction in conservation had outlived its usefulness, as its 'accounting approach' offered no 'wise or workable solutions', and instead provided descriptions of ecological destruction 'as a means of drawing the attention of humanity' [32]. To move beyond this paralysis, these writers pleaded that conservation biologists join forces with other researchers and non-scientists, to 'offer humans the means to envision a positive and achievable vision of the future—one that details how the world should look for their children and all children to come'. Twenty years on, the uptake of that call for a new research agenda remains modest. However, some have pushed to expand the range of positive plausible, desirable and projectable pathways and scenarios that we might envision for living with future environmental conditions [33,34]. This includes the Seeds of Good Anthropocenes initiative (goodanthropocenes.net), which collects examples of positive initiatives, cases and projects to 'counterbalance current dystopic visions of the future that may be inhibiting our ability to move towards a positive future for the Earth and humanity' [35,36].

Our contribution to this research agenda, intended to bolster discussions and research efforts, centres on the need for nuancing the meaning and possible implications of biodiversity change, especially where it concerns human habitation of the Earth. For instance, a more fine-grained interrogation of the 'sixth mass extinction' claim/narrative reveals that human-driven species losses (and indeed gains [37]) are spatially, taxonomically and temporally uneven [13,38]. Projections of future losses are highly variable and dependent on the unit and scale of measurement (genetic, species, landscape, temporal lens, etc.) as well as the method of analysis and built-in assumptions of future extinction risks for different groups [39,40]. While the current trend of species threatened with extinction clearly represents high percentages for some groups (e.g. amphibians 41% of species, cycads 71%, sharks 37% [41]), there is much debate and uncertainty on whether the present and ongoing human-associated 'event' will constitute a 'mass extinction'i.e. (75% species losses in under 2 million years—a relatively short period of (geological) time [25]), but extremely long-term according to dominant (Western) conceptions of time in vernacular use. The extent to which reductions in total diversity and (often) localized species losses might affect ecosystem processes such as primary production, soil nutrient cycling, herbivory and predation, is also unclear.

Research analysing biological monitoring data collected over the past 50–100 years has shown that at the regional or national scales (e.g. of a country or state), there has been either no change or increases in certain measures of plant biodiversity across the vast majority of locations investigated [42]. Although species turnover in ecological communities has increased (changes to individual species within a community in a given location have accelerated), the average community richness of those same locations has remained largely static [43]. On top of this, net primary productivity (NPP) in low-productivity ecosystems has been shown to increase with human modification and has been associated with concurrent climate and pollution side effects [44]. Despite many global measures of biodiversity showing an overall decline, these regional increases in biodiversity and a lack of local changes do make sense. Increasing transport of species across the globe and the disturbance of ecological systems by human activities provide a wider range of dispersal opportunities for different taxa, which boosts regional diversity measures. In many cases, at the local scale, species losses may (on average) be balanced by species gains [43,45–54].

Thus, the near total loss of some current major biomes, which some studies have projected [55,56], could also be read as biome *change*. In other words, a different or novel composition and distribution of global biomes and species communities may emerge, not barren or lifeless landscapes [57,58]. This is recognized in the reconciliation of individualistic versus superorganismic debates in 20th century ecology [59,60], which views communities through the lens of a set of species that each reacts individually to environmental change [61]. For instance, following the onset of the Holocene, the emergence of entirely novel agricultural systems (that now cover approx. 50% of the presently habitable terrestrial Earth surface [36,62–64]) resulted in biodiversity gains in as many locations as losses, through to 1850 CE [11]. Change is demonstrably the norm, not the exception.

Although today the speed and magnitude of change exceed rates estimated for the vast majority of the past (where it occurred on millennial and geological timescales), there is an unprecedented capacity to mobilize knowledge and resources to understand, anticipate and, in theory, respond effectively to change [65]. Yet translating this capacity into effective action is evidently not happening. Moreover, for those who experience change, it may be understood as a visceral *loss* of intrinsically meaningful and instrumental ecosystems and services in living memory. We do not typically experience the loss of historic and especially prehistoric landscapes or services in the same way, although deep cultural memories (e.g. for decolonizing Indigenous peoples) often persist. Now we face inexorable, rapid, collective, planetary ecosystem change, which implies a need to recalibrate how we understand and frame biodiversity change in productive ways.

These are important gaps and nuances to consider in research so that its conclusions are framed in ways that constructively inform policy, practice and public understanding to avoid either the paralysis of crisis narratives or overlooking the harmful impact of change today.

3. Tipping point and boundary narratives

Such insights challenge the assumptions, evidence and reasoning behind social or ecological 'tipping points' or Earth system boundaries and their implicit trajectories towards ecological and civilizational collapse and human extinction [66]. Tipping points and 'safe operating spaces' are far more complex and imprecise than such binary or 'mathematical' portrayals [57,66–69]; there are differences between an accelerating rate of ecosystem change and extinctions, and 'regime shifts' to alternative stable (social–)ecological states [58]. For example, sea level rise is not 'abrupt' as a tipping point infers, but occurs slowly over annual to decadal or greater timescales. The prospect of an Atlantic Meridional Overturning Circulation (AMOC) shutdown and the interactions between planetary boundaries are very difficult to quantify, downscale and govern [57,70,71]. Today's food systems are complex and may not always require high biodiversity to sustain a world population of more than 8 billion (albeit inequitably) [72–74]. This suggests that high species losses may not necessarily prevent the provision of sufficient food globally. That biodiversity losses translate eventually, or imminently, into global or local societal disintegration is not an obvious conclusion.

Numerous examples from the archaeological literature contest collapse narratives and provide hope and possibilities for action, in particular for illuminating and supporting the underpinning conditions for adaptation and resilience [75]. Indeed, many collapse narratives suggest a tipping point between biodiversity loss and persistent human existence. For example, the much-cited fables of Rapa Nui (Easter Island) or Mayan collapse have largely been shown to be false conclusions drawn more from preconceptions of Indigenous communities than from the archaeological record, which instead indicate continuing presence and resilience [75]. The relative speed of recovery from a shock in a social system can provide clues to changes that may be more transforming than annihilating in nature, with lessons that can inform action today [76].

Other research reminds us that change is intrinsic to behaviour, ecosystems and societies, so while losses are obviously occurring, they do so against the backdrop of a transformative 'counter-movement for real and historical social–ecological change' that is 'building momentum' [77] but not yet fully manifested. The next section considers social–ecological–technological systems as a productive way of understanding human responses to biodiversity change that capture these nuances and help us envision just and viable societies amid such change.

4. Social–ecological–technological systems

The social–ecological–technological systems (SETS) lens (figure 1) emerging in (urban) sustainability research [78–80] is useful for helping us understand the co-evolutionary nature of interactions between human and ecological systems [81–83]. Social (**S**) in SETS is shorthand for 'social–cultural–economicgovernance' systems, which incorporate culture, law, governance, power and inequity considerations [78]. Ecological (**E**) likewise describes the climate–biophysical–ecological systems, with the technological (**T**) meaning technological–engineered–infrastructural systems, including things like buildings, energy, transportation, information technology and communications [78,84,85]. Some systems, like agriculture, overlap as they involve policy, technology and land use. The SETS framework, typically applied at the city scale, proposes that 'all ecosystem services are fundamentally influenced by the interaction of all SETS dimensions' dynamically in 'ecosystem services provisioning' sothat 'the relative contributions shift in time and space' [78]. What this means is that **S**, **E** and **T** systems and their component parts (technologies, people and societies, species) can rapidly evolve and drive evolution in each other, such as in the urban settings from which the SETS concept grew [78,83].

The SETS framework is argued to be particularly useful for envisioning pathways to positive human futures and understanding issues around scaling local initiatives to global change [78,84,85]. This framework allows different kinds of coupled system relationships (social–ecological, social–technological and technological–ecological) to be considered in relation to a given policy, practice or phenomenon. These can be used to reconsider 'growth…efficiency…the state…the commons…and justice' issues in relation to environmental change [80].

Further, the SETS approach permits a recognition of new forms of agency emerging in the technological realm with ecologically impacting and geologically enduring built infrastructure and materials, together with the advent of artificial intelligence (AI). Built environments are still human-produced, at least so far (with AI & robotics in the offing), but they are increasingly bound to ecological issues [79]. Server infrastructures for the internet and AI have ecological impacts and AI is applied in ecological management scenarios, creating both new risks and opportunities [86]. Built environments can make use of nature-based solutions, structures can intentionally or unintentionally host species and ecosystems, and materials and structures can endure for centuries or more [87]. This blurring of boundaries between SETS categories may help us to explore ways that losses in one domain may be offset by compensatory gains, substitutes or alternatives within the same or another domain. Importantly, these evolutionary dynamics do not have to occur at very slow or geological timescales, but can instead happen quickly.

A place-based SETS is useful for understanding the habitability of a location, understood as how many people might live there and the conditions they experience under given SETS conditions [78]. For example, if loss and damage to ecosystems exceed the limits of protective infrastructure and trade access to ecosystem services in distant regions, the community may be forced to relocate [88] because the place is *technologically* uninhabitable, or compellingly less desirable to inhabit than other potential locations. Such relocations are often grossly unjust, with lasting harm to people who have been forcibly relocated (e.g. via colonialism or disasters), or otherwise migrated, and the adverse impacts of the unmitigated displacement on individuals and communities are well known [89]. But this is not universal, and the emergent interaction between people and place—the SETS conditions in the destinations—shape the nature of outcomes, which can change intergenerationally [89].

In addition, uneven local variation in habitability does not necessarily translate to an uninhabitable planet. But it does raise the prospect of the large-scale adaptive transformation [90] of human settlement patterns across the Earth. Facilitating safe and just adaptive mobility at large scales over uncertain timescales amid a 'fluid' [89] environment raises critical questions about the meaning and practice of equity, justice and wellbeing, especially where these are closely tied to territorially rooted and deeply meaningful political or cultural institutions [91,92]. Moreover, it raises questions about how to navigate and prioritize between different priorities and scales of justice, e.g. between human generations and threatened species.

Next, we highlight examples from the archaeological record that describe novel ways in which societies have responded to substantial changes in ecological/climate conditions. We show how these societies varyingly mobilized domains of SETS to different degrees, often using one domain to compensate for deficiencies in another.

5. Learning from past human food systems in different biodiversity contexts

The quest to find or cultivate food, which is essential for survival, is perhaps the most significant way in which human societies interact with and shape their environment. Access to food (and water) is necessary to inhabit a location and is closely linked

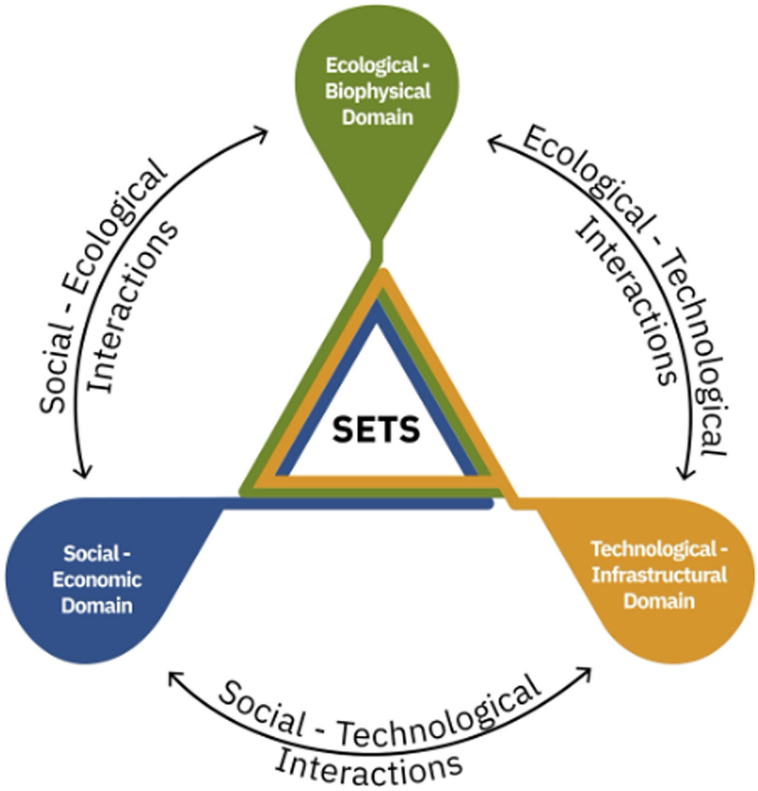

Figure 1. Social–ecological–technological system (SETS) showing the interaction between the ecological, social and technological domains (CC-BY-ND [78]).

to social, ecological and technological conditions, making it a useful example for exploring biodiversity questions. Despite our many remarkable technological advances, human survival still ultimately depends on obtaining sufficient calories and nutrients from our environment. Indeed, it is largely through successive waves of agricultural innovation that human populations have been able to expand—albeit to SET limits [93]. However, our food systems have also been one of the dominant forces shaping global biodiversity—from prehistoric megafaunal extinctions driven by hunter–gatherer societies [94,95] to the current industrialized food system that is the primary driver of global biodiversity losses [96,97]. For these dual reasons, food systems are a useful lens through which to consider the human capacity to transition to new regimes by responding, adapting to and shaping changing climates and biological communities.

While a food systems framing necessarily emphasizes the instrumental role of biodiversity in sustaining human nutrition and survival, it also implicitly encompasses a wider set of socio-cultural and biocultural values, since in many societies food production, sharing and gathering are central to cultural identity, social cohesion and spiritual practice, making food systems a particularly rich lens through which to understand the evolving nature of human–nature relations within and beyond their material dimensions. The following examples, spanning effectively the full range of absolute latitudes and climate spaces, highlight the variety of pre-industrial (human) food production systems used over the past millennium and cover a broad spectrum of ecological and cultural contexts. They exemplify the characterization of societies as embedded in SETS, highlighting the changing relative contributions of each SETS component across different contexts as these societies sustain or transition into new modes of living with their environments.

(a) Complex hunter gatherers, Pacific Northwest

Following the onset of the largely warmer and wetter conditions that marked the end of the last glacial period approximately 12 ka, human populations across the globe shifted away from foraging wild resources towards cultivating and rearing a small number of domesticated plants and animals [98]. Based largely on excavations from the Near East and later from China, the emergence of 'complex' (sedentary, hierarchical, surplus-producing) societies and the establishment of full, settled agricultural economies were historically (and incorrectly) assumed to be necessarily linked. Despite this, archaeological and ethnographic work across North America (and elsewhere, e.g. [99]) has shown that complex societies developed in the absence of full agricultural economies—most notably in the Pacific Northwest region of North America, where large, socially differentiated populations heavily relied on wild resources from the intensely productive forests and rivers up to the time of European contact. Salmon fishing provided a major subsistence component for these populations, facilitated both by knowledge of salmon life cycles and also by specific technologies such as smoking and drying that allowed resources to be used over the leaner winter months [100–102]. 'Forest gardens' containing nut-, berry- and fruit-producing plants were also deliberately cultivated to supplement seasonally foraged resources [103–105]. Indeed, today these forest gardens—now largely abandoned following the forcible expulsion and 'assimilation' of Indigenous peoples—represent 'islands' of substantially higher biodiversity than of the surrounding forest [106]. In the highly productive landscapes of the Pacific Northwest, human populations employed a subsistence practice different from the majority of Earth's populations at the time, while living in social groups no less complex.

(b) Wari empire, South America

Approximately coeval with these Pacific Northwest forager-fishing cultures was the establishment of South America's first 'empire', the Wari (600–1000 in the Common Era (CE, or year 0 to present), located in the coastal and upland regions of present-day Peru [107]. To overcome the severe aridity (25 mm annual precipitation [108]) and the extremely low productivity that characterizes these landscapes, Wari rulers, through enormous, state-led labour mobilizations, developed complex water engineering systems to provide essential water resources for the capital (Wari) and feed the expansive agricultural lands of the empire's many colonial outposts. At the frontiers of Cerro Baúl and Pikillacta, major canal and reservoir networks ferried winter rains and glacial meltwater towards urban centres and maize- and quinoa-producing gravel and earth terraces. These terraces, each a metre tall, transformed the arid landscape into a productive agricultural system that covered approximately 1000 ha and was engineered to conserve water, prevent soil erosion and enlarge the surface area available for production [109]. A combination of factors at approximately 1000 CE—including sociopolitical stresses and perhaps some role for prolonged drought—led to the demise of the Wari [110,111]. In the present-day, however, local people are 'rediscovering' Wari water management techniques as effective methods for combatting increasingly uncertain and unreliable water resources driven by accelerating climate change [108]. The impressive hydro-engineering works of the Wari were an innovative technological development that facilitated habitability of the apparently difficult ecological conditions that characterized the region, resulting in the expansion and flourishing of South America's first imperial power, one that lasted 400 years.

(c) Sámi, Northern Europe

Representing Europe's only Indigenous population recognized as such, the Sámi people inhabit the most northerly extents of Norway, Sweden, Finland and the Kola Peninsula (Russia), a region covered by snow for up to eight months of the year and of comparatively low biodiversity. Yet this region has been inhabited by humans for approximately 10 000 years [112], with the archaeological record over the past few millennia suggesting Sámi subsistence was based on fishing and hunting reindeer [113]. Dates are debated, but between approximately the 9th and 15th centuries, many (but not all [114]) Sámi populations transitioned towards a nomadic pastoralist mode, with a primary focus on semi-domesticated reindeer herds, a transition probably driven by a combination of climatic changes (decreasing temperatures during the Little Ice Age, c. 1300-1850 CE) and social changes, including changing tax regimes and increasing settlement of the region by non-Sámi peoples [115,116]. In the low or fluctuating productivity landscapes of the European Arctic, reindeer provide Sámi people with a variety of essential products, with the relatively recent shift towards mobile pastoralism and domestication. Social innovations also facilitated the endurance of the Sámi's lifeways in some locations, with Sámi populations exchanging reindeer with non-Sámi populations in return for being hosted on farms during the winter months between the 17th and 19th centuries in Sweden.

Over the past approximately 12 ka, human societies across the planet developed diverse food production strategies that were adapted to their local ecological, climatic and societal context—the Wari water engineers, the Pacific Northwest foragers and the Sámi pastoralists being some CE examples (along with numerous other examples [117,118]). These diverse practices resulted in the major and often rapid transformation of terrestrial (and later, marine) [119–121] ecologies across the planet [122]. In the case of both food production and, later, urbanization, these human-driven ecological transformations provided beneficial ecological conditions for future generations—an 'ecological inheritance' [123]. In turn, these ecological inheritances, and the (fitness) benefits they provided, reinforced the selection of these same behaviours in further generations [124], which resulted in the proliferation and expansion of these ecological conditions and associated behaviours over time. This process, facilitated by the unique capacity of humans for social learning—*human sociocultural niche construction* [125]—has resulted in the exponential expansion of 'novel' environments, such as croplands, grazinglands, mixed agricultural landscapes and urban landscapes, across the Earth's surface over the past 12 millennia.

A number of abiotic changes, including climate change, land-use change, pollution and nutrient alterations, can take existing ecosystems into non-analogue space [126]. All of these have and do result from many of the common interactions between human societies, technologies and ecological systems. In many of these cases it is not possible to return affected ecosystems to a past state and such past states may not be viable in the new conditions [127]. It may also be highly undesirable to do this because, as discussed, societies may rely on these altered systems for food production or other resources. Biotic changes in the species present in these systems are often seen as a negative for biodiversity but this is often crucial to the maintenance of ecosystem processes [61]; indeed, many species have prospered in highly human-modified systems [128].

These once-novel, but now pervasive Anthromes now dominate the Earth's surface [122] and its processes [129,130]. Over the Holocene, these place-specific food systems and the broad diversity of crops provided human populations with their nutritional needs and a means to organize human labour in its production [131,132]. Strikingly, it was these human food production systems that probably also generated the observed biodiversity gains in multiple locations over the past approximately 8 ka—through small-scale disturbance of vegetative communities [11] and the introduction of novel nutrient cycling dynamics [133]. Yet, since the industrialization of agriculture after approximately 1800 CE, its subsequent intensification and the globalization of food markets, these place-specific food systems have been marginalized. Today, wheat, rice and maize represent between 50% and 60% of all calories consumed globally [134] and over one quarter of the food produced is traded on the global market. Mosaics of 'natural' vegetation interspersed with low-intensity cultivation and grazing have now largely been replaced with monocultures of crops maintained with large quantities of artificial fertilizers and pesticides, with overwhelmingly negative impacts on biodiversity [96]. These food products are also now less nutritionally dense than those that came before, with lasting and ongoing consequences for human health and wellbeing [135]. They also create intensely fragile dependencies on global supply chains, with states reliant on free-flowing trade for social stability and the survival of their populations [136].

The current globalized food system has emerged, in some ways, out of necessity, with billions of people to feed across the globe. Pre-industrial-style, small-scale, mixed and extensive agricultural systems would be unable to meet this demand. Thus, in some ways, our current system has been a success (supporting billions, albeit inequitably), though often—but not always—with detrimental to catastrophic effects on biodiversity across the globe. Looking forward, the trajectory of our global food system is likely to be one of the most important factors shaping future scenarios of biodiversity and climate. With agriculture covering about 50% of the Earth's current habitable land surface and contributing one quarter of greenhouse gas emissions [63], novel food production systems surely provide one of our greatest levers over the future of the biosphere. These examples from the archaeological record can provide inspiration for a global food system that is sufficiently productive but without the current pervasive harmful effects on the biological world. They highlight how radical new socio-ecological technologies can alter societies and the environment in dramatic and unforeseen ways. They also underline the importance of social innovation and collective action in the face of changing and/or harsh biodiversity/environmental contexts. Thus, in the future, if technological progress keeps pace [137] then food will be produced in new ways using novel and emerging technologies—e.g. synthetic carbohydrates, gene edited crops and livestock, or laboratory-grown meat—in combination with smaller scale, place-specific agricultural or agro-ecological systems [138] and new socio-political structures (at different scales). Together, these can provide the backbone for sustainable and equitable food systems adapted to a changing climate and ecology [31].

But this is inherently a speculative exercise, given that currently the global industrialized food system still reigns and many of these technologies or initiatives are in their infancy, having neither been scaled nor costed for energy demand, financial burden and their contribution to inequity. It is worth noting that the archaeological examples described were not utopias of justice and equity; they were (in the cases of the Wari and the Pacific Coast peoples in particular) highly stratified societies, characterized by inequality. Despite this, we can draw out the helpful elements from the archaeological record, while learning from those elements that we do not find helpful, to assist in collectively envisioning and inspiring desirable futures.

(i) Present

Adaptations, commonly meaning activities undertaken proactively or reactively in response to changing or anticipated conditions, are not neutral and they mean different things and present trade-offs across contexts and temporal and spatial scales [139–141]. Like historical environmentally driven migrations, today we see voluntary and involuntary migration linked to environmental change, which is especially pronounced in drylands and in response to comparatively rapid onset shifts in climate regimes [142]. This is broadly a social adaptation (some would argue a last resort). However, there can be problems when destination locations adopt policies hostile to migrants or when migrants use skills and knowledge (e.g. relating to agriculture) that are unsuited to their new context. We also see a resurgence of extensive farming methods [143] that are adapted to changing environments as well as technological innovations to both mitigate and adapt to changing environments, some of which include synthetic materials such as built infrastructure, or nature-based solutions (NbS) harnessing ecological processes [144]. For example, emerging technologies such as gene edited crops, and vertical, urban farming practices, can reduce land use footprints, while agro-ecological farming approaches can maintain productivity whilst improving biodiversity outcomes [145]. Desalination technology provides water to populous, high-income societies in arid regions; however, it relies on abundant renewable energy and creates waste disposal challenges. Desalination is therefore partially disconnected from regional ecological or climate change, with low impact on terrestrial ecosystems but with impacts on local marine ecology [146]. Cultured meats offer potential to spare land for biodiversity, but they currently suffer from a number of uncertainties and trade-offs [147]. Social arrangements such as more equitable and complementary land tenure, governance, labour practices and structures provide further examples of possibilities [148]. And for the first time, teleconnection via transportation, life support and communication technology has allowed small but increasing numbers of humans to draw on the Earth's ecological resources to survive in the space environment, which is otherwise inimical to life, showing that we have the capacity to sustain human life technologically in otherwise sterile environments. These examples, as well as practices documented in the Seeds of Good Anthropocenes or Biosphere Futures (biospherefutures.net) and movements like Conservation Optimism (conservationoptimism.org), provide contingent positive examples of socio-technological or ecologically focused efforts that make the most of emerging conditions.

A warning for the present, however, comes from the Sámi as their past adaptations and resulting bio-cultural systems are contingent on enabling conditions that, today, are at risk from changing social and political processes. The lifeways of the Sámi and many other pastoralist peoples are dependent on mobility across vast landscapes to meet their needs under varying conditions, but this access is eroding through landscape fragmentation and privatization [149]. Recognizing how these historic adaptive conditions inform the present is crucial to understanding adaptation now and for transitions towards positive and viable futures.

(ii) Future

Long-term scenarios are often used to envision future global environmental change in accordance with different socioeconomic trajectories of human development and policy choices [150]. Perhaps the most prominent examples of such scenarios are the widely adapted Shared Socioeconomic Pathways (SSPs) [151,152] that are often linked to greenhouse gas emissions pathways (e.g. Representative Concentration Pathways [153]) to indicate a relationship between forms of global [33,84,85] development and warming levels. SSPs consist of a spectrum of five future narratives based on relative challenges to collective action on climate change. These range from Sustainability (SSP1), involving high equality and global cooperation to rapidly reduce greenhouse gas emissions and keep warming low, to SSP2 and SSP3, involving competitive multipolarity and inequality with increasing warming, through SSP4 and SSP5, where development is still led by fossil fuel use and high warming. The SSPs are predicated on development pathways within the social and political norms and institutions of recent historical trajectories, but they do not explicitly envision worlds outside of this system. Declining biodiversity is likewise predicated on historic perspectives and has been equated with an existential threat to humanity, at least at current population levels [26]. While positive transformative visions are often offered [33,84,85,154], it is still rare to see them accompany explicit projections resulting from missed low mitigation/high conservation thresholds or targets; e.g. of a thriving, cooperative, human future on a hotter, low-mitigation and ecologically changing planet (but see e.g. [155]). Some projections counterintuitively, however, show local gains or lower declines across multiple regions and ecosystems, even under extreme warming scenarios [156,157]. Research in this area is still very limited [158], but the prospect of lower biodiversity loss or gains under higher warming, or increasing ecosystem services despite losses, implies a still habitable Earth, able to provide fundamental ecosystem services for human populations despite the fact that such gains might be heterogeneously distributed [159].

It is increasingly important to explore the space created by such projections as we edge past politically determined sustainability horizons to live in circumstances that we have not yet envisioned. Here, new modelling of biodiversity scenarios under different explorative scenarios (*what could happen*) is relevant. Such modelling will help to inspire positive collective action so that the perceived 'failure' of missing such targets does not lead to policy and action paralysis. This does not mean that we should stop or discourage current target-seeking scenario efforts centred around nature and its contributions to people [160], but we can and should also envision positive futures beyond those boundaries. We stress that failing to explore future ecologies means we will deny ourselves the opportunity to shape them actively by helping the biosphere adapt to the elevated rates of change. It is critical in this context to note that inaction is, in itself, an action with costs and consequences [161].

First steps in this process involve more sophisticated modelling efforts to construct a clearer sense of the possible nature and distribution of biodiversity losses and, more importantly, gains on a warming Earth so that we might imagine living there, as few such projections so far exist. Models that do exist are coarse and prospective, but instructive in that they help us conceive of futures involving significant changes in the existence, size and location of major biomes and food growing regions, but not in their absence [55,56]. For example, the loss of coral reef ecosystems, the replacement of most of the boreal forest, and transitions, such as from forests to drylands in regions like the Amazon are projected to occur over the next 500 years under lower mitigation scenarios [31,55]. These projections do not indicate the disappearance of ecological landscapes and their biodiversity, but their change. Read another way, a changing local ecology means changing local and regional provisions of food, water, energy and ecosystem services, not their disappearance. In 500 years' time, it is plausible that what we lament as a tragic loss will be viewed differently by the society that lives in or uses that location at that time. At a global scale, this translates into regionalized losses and gains depending on the evolution and interaction of SETS factors over time.

In whatever future we envisage, food production will need to take a central role. Given that agriculture covers around half of the world's currently habitable land surface and is the primary driver of biodiversity loss [6], it is probable that agricultural transformation will achieve our most dramatic future impacts on the biosphere. In other words, this is our biggest lever and will probably have a disproportionate role in setting the course of our future trajectory. Here we can also draw on the deeper human past, where the span of time shows us that humans have always adapted to local conditions then moved around the Earth, displaced and driven by push and pull factors including but not limited to environmental change, albeit in far fewer numbers than today. The modern *global* set of state-centred institutions and norms (e.g. those commonly understood to have emerged following the Peace of Westphalia in 1648 and United Nations and Bretton Woods institutions from 1944) that fix humans within specific geographic locations based on perceived differences in culture, ethnicity, religion and style of government is a relatively recent phenomenon. These institutions are often dominated by short-term future outlooks, such as election and economic cycles, international trade or even survival and meeting simple day-to-day needs. Thus a key condition of adaptation and resilience to environmental change, when examined from this long view, is recognizing and accepting our fluid location in space and time in a period of self-induced, accelerated, global environmental change and matching our institutions accordingly.

6. Discussion

Our argument distils into a new research and practice agenda centred around measurement, framing, learning, imagination, and justice and equity.

(a) Measurement: what and how we measure matters!

Biodiversity research must consider gains, evolution and novelty, as well as losses under present observations and different projection scenarios to provide a more complete picture of the changing and future biosphere. This will allow more careful calibration of what we mean by mass extinction, loss and decline, as well as their implications, and will lead to better understanding of the distribution of biota, biomes and potential ecosystem services that people may draw on in the future. Importantly, we must also focus research attention on places of novelty and gain so that we might better grasp the services or contributions to people (both desirable and undesirable) that these areas might provide now and in the future. Doing so will help local and global decision-makers and publics understand the scope and scale of change.

(b) Framing

It is critically important to use appropriate framings. If we accept that the environment, technology, and society are rapidly changing, we need an overarching framework, or perhaps at least a complementary set of frameworks, that helps us see and respond to those changes effectively. We have proposed SETS, as it is a 'big tent' idea that is able to capture the dynamic and nonlinear interactions between 'fluid' social, ecological and technological domains that determine the ways we might adapt (or maladapt) to different kinds of change. SETS thus can describe a much wider range of just and realistic pathways and scenarios than we currently have. SETS may be especially useful in capturing the very rapid rise of technologies like AI, the development, applications and implications of which are very difficult to predict [86].

(c) Learning from the past

We have provided examples to show how human societies of the past were able to mobilize different social and technological elements to adapt and thrive amid changing environments, including those that became increasingly challenging. Rather than focus on near-term, late-Holocene or pre-industrial 'baselines' from which to calibrate measures and understandings of environmental change and adaptation, we might look to our deeper past in the archaeological record to draw out lessons and inspiration for learning to live with a changing Earth in ways that are place-based and over longer timescales [162].

(d) Imagining alternative futures

As we seem increasingly likely to miss our current climate and biodiversity conservation policy goals and aspirations, we must draw our attention to living justly within the world(s) available beyond those missed targets, even as we redouble our efforts towards mitigation and adaptation. This involves radically revising the current crop of SSPs and other scenarios that correlate lower mitigation with lower adaptation and with greater inequality and conflict. We must develop and communicate practical, participatory, evidence-driven scenarios for a just and thriving society on a hotter Earth with a novel ecosphere, asking what social and technological systems and structures might be conducive to such a society and how we might create them [33]. This requires equitable processes, as well as equitable outcomes—which are especially important amid periods of major political changes.

(e) Justice and equity

Justice and equity are central to envisioning biodiversity futures on a changing Earth. The projected future of a redrawn global ecology very probably directly challenges the historically rooted cultural and political ties to landscapes that translate into territorialized (i.e. community, nation-state) political economies and cultural identities underpinning place-rooted regimes of inequity and conflict, as well as emancipation and justice. Not everyone is mobile: migration and displacement bring new challenges and they may reduce the adaptive capacity of the origin or lead to conflict in the origin and/or destination. Losses of place are deeply harmful to individuals and cultures with ties to those places, at least in the present and near-term periods [163], and they can occur without human movement as social and cultural values and ties to the environment alter. While migration and change are also the prehistoric norm for human presence on the Earth and may seem benign in the abstract of prehistory, those experiencing change within their lifetimes may have a very different experience, the aftermath of which can last for generations or even centuries if cultures and institutions disadvantage the displaced, as seen in colonial legacies.

Urgent questions result. What is justice (e.g. decolonial land-back and self-governance) and injustice (e.g. forced displacement, territorial annexation, social vulnerability) when the underlying landscape profoundly changes [66]? Where are the levers for just and equitable process of meeting food (and water and energy) security amid rapidly changing SETS? This may mean a challenging but perhaps essential project of answering profound questions about the *human condition* when ecology and technology change so rapidly, and accepting the losses of species, landscapes, climate regimes—how do we avoid maladaptation traps [164]? Justice and equity questions must be central to a research agenda of living on changing Earth.

7. Conclusion

Humans undoubtedly have the capacity to adapt to perceived 'negative' changes in the biosphere, and to enable the adaptation of species. We are also—perhaps uniquely—able to take advantage of rapidly changing ecological/climate conditions; be that colonizing new continents approximately 100 ka in light of changing precipitation regimes, or, crucially, the development of agricultural systems that, for better or worse, evolved into today's cultures, societies and global civilization. Exactly how our present-day perceived challenges (of climate and biodiversity change, water, land, food and food system vulnerability, etc.) affect the scope of futures available to us is largely unknown. But the archaeological record demonstrates that 'crises' often serve as a bridge to a further chapter in the human story, though admittedly that may be much harder to see for those living through these events [165].

The scale of the Anthropocene event is planetary but is experienced locally at timescales of hours (e.g. extreme events) to centuries and millennia as the climate warms and weather patterns, species, biomes and human cultures change. There are a range of social, ecological and technological tools to help (and hinder!) us as we navigate the unfolding Anthropocene event, and new tools and barriers will continue to emerge. Though ecological change is presently more rapid than past periods (and our reference knowledge is accordingly limited), so too is the human ability to recognize its impacts and bridge to new modes of living to keep pace with change. This is an important insight as we consider future projections of environmental change, and the scope of possible, plausible and desirable futures on a changing planet. But doing this means we must accept fundamental and profound changes that depart from our historically derived cultures and institutions, and focus on safeguarding and bolstering the conditions that enable adaptation and innovation. Perhaps this means adapting our goal-rationalist institutions and senses of self and place that govern human and environmental affairs [166] towards new politics, laws and cultures for governing a changing Earth [166]. Earth stewardship scholarship, for example, has for many years proposed that such crises offer opportunities to restructure global governance [167]. But this task is challenging as it means we must recognize—and accept—the reality and implications of a rapidly changing biosphere for our mode of living. Only by doing so might we begin to identify pathways and build adaptive institutions for a globally just transition to living on a different Earth.

While we argue that there is an urgent and increasing need to socially and technologically imagine a thriving and just society adapting to living on a hotter and ecologically transforming Earth beyond our preferred limits, there still remains a critical and urgent parallel need to maintain and intensify climate mitigation and biodiversity conservation efforts. Failure to do so will erode adaptive capacities and reduce available pathways towards just and safe spaces for humans and other species.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. This article has no additional data.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

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