Humans could become the greatest driver of biosphere net gain in Earth history, but we are currently the second fastest driver of biosphere loss

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Human activity is transforming the shape, size, and resilience of Earth's biosphere, degrading and augmenting Holocene baseline conditions at various scales, and replacing the wild biosphere with an anthropogenically modified one. We evaluate episodes of biosphere change throughout Earth history and compare them with contemporary and near-future anthropogenic changes, developing the concept of *biosphere disruptors* – agents that force global-scale macroevolutionary change. *Transient disruptors* are short-lived agents (mean 8.0×10^5 years), including massive volcanism and asteroid impacts. *Persistent disruptors*, including atmospheric and ocean oxygenation and land plant evolution, remain in the Earth System over long timescales (mean 1.6×10^8 years). In the geological record, *transient disruptors* are associated with temporary but sometimes massive biosphere degradation, whereas *persistent disruptors* are associated with sustained biosphere enhancement. Most anthropogenic biosphere impacts resemble those of past *transient disruptors*, globally degrading wild biomass and biodiversity. Humanity is driving the second highest rate of biosphere degradation in Earth history after the Cretaceous-Palaeogene bolide impact. However, humanity is the first disrupting agent capable of reflecting on and potentially transforming its impact on planetary habitability. If we can achieve this, humanity could drive the greatest rate of increase in planetary habitability in Earth history on centennial to millennial timescales.

1. Introduction

Seven of the nine planetary boundaries that determine a safe operating space for human interactions with Earth's life support systems have already been transgressed by human activity (figure 1) [1]. The biosphere integrity boundary has two components, genetic and functional integrity, which have both been transgressed over the last 150 years [2,3]. The functional integrity boundary represents the biosphere's capacity to maintain ecological functions and was breached in the late 19th century when the proportion of global net primary productivity used by humanity (human-appropriated net primary production [HANPP]), began to exceed 10%; by 2023 HANPP had increased to ~30% [3]. The genetic integrity boundary measures extinction rate and is set at fewer than 10 extinctions per million species years (E/MSY) [2]. The genetic integrity boundary has been far exceeded during the last 150 years, with the current value exceeding 100 E/MSY [3]. Since the late 19th century there has been a ~10% loss of genetic diversity and a global extinction rate that is tens to hundreds of times greater than the background level [1,4]. The Living Planet Index shows a similarly diminishing pattern for the biosphere, with monitored vertebrate populations decreasing by an average 73% of their 1970 value by 2020, mirrored by declines in invertebrate groups such as insects [5,6].

Human influence on planetary function increased rapidly during the onset of the 'Great Acceleration' of the mid-20th century (e.g. [7–10]) and is clearly continuing to change Earth's life support systems in the 21st century (e.g. [1,3]). These changes have been predominantly driven by humans in hyper-consuming societies, rather than humanity in total [11,12]. Over this time, most of Earth's terrestrial surface, as well as its atmosphere and oceans, became pervasively influenced by humans (e.g. [13,14]). Agricultural production greatly increased in the 20th century and is thought to be the cause of ~70% of terrestrial biodiversity loss [15] with land area covered by primary vegetation falling from ~70% in 1850 to <40% in 2000 [16]. In the marine environment, about one-third of all fisheries are now unsustainably exploited following a steady increase of unsustainable fisheries from about one-tenth in 1970, though there has been an increase in the proportion of underfished stocks since 2019 [17].

Humans have driven massive increases in terrestrial productivity and mammalian biomass. Through population growth and livestock farming, humans have approximately tripled the total biomass of mammals since 1850, including an ~500% increase in domesticated livestock, but this has come at the cost of massive reductions in wild mammal biomass (~60% loss of wild terrestrial mammal biomass; ~70% loss of wild marine mammal biomass) [18]. Conservation can counteract some of the losses in the wild biosphere, and conservation efforts have halted and substantially reversed some regional population declines, including range expansions of some species [19]. Moreover, some land management practices have been shown to benefit both human societies and the local wild biosphere [20], including matrix farming (e.g. [21]), patch-burning (e.g. [22]), and sustainable fishing [23]. Technological developments also provide space for the evolution of novel ecologies (but see [24]), and some local biodiversity increases have been driven by deliberate or accidental anthropogenic species translocation and hybridization (e.g. [25]).

From the perspective of long-term planetary evolution, the question is: *how do anthropogenic changes to the biosphere compare to past intervals of biosphere change*? We suggest that lessons drawn from large biotic changes in Earth's geological past can inform the actions necessary for humanity to augment planetary habitability, here used in the sense of Earth's capacity to support life in a way that maximises across all of functional and taxonomic biodiversity, productivity, biomass, and resilience [26]. Maximising only one of these (e.g. increased productivity through algal blooms) is not sufficient to enhance planetary habitability. Similarly, high resilience alone does not imply greater overall habitability – high resilience implies a systemic resistance to transformation or change of state (e.g. [27]). Where a resilient system state corresponds to low biodiversity, productivity, and biomass, the resilience of that state is undesirable in terms of planetary habitability, hindering pathways to increased biodiversity, productivity, and biomass. In the language of social and ecological resilience, such a state has undesirable resilience [27], with low diversity, low productivity, and low biomass becoming locked-in for long intervals.

To address how anthropogenic biosphere changes compare with biotic changes through Earth history, we first identify intervals of macroevolutionary change in the geological record (tables S1-S5). We then assess the duration (figure 2; tables S3-S4) and impact (figure 3; table S5) of these intervals on the biosphere. We also resolve the driving mechanisms behind these intervals into two categories – *transient* (table S1) and *persistent disruptors* (table S2).

Transient disruptors are typically geologically short-lived, ephemeral, agents. Our data show that *transient disruptors* tend to leave the biosphere with lower functional and taxonomic biodiversity, biomass, and productivity, locking in a metastable state of undesirable resilience [27] while they are present in the Earth System (figure 4). Biosphere recovery, reorganisation, and/or transformation to a new state of more desirable resilience typically takes several million years after the disruptor and its effects have dissipated from the Earth System (e.g. [28]). In contrast, *persistent disruptors* are geologically long-lasting and remain in the Earth System beyond the interval of their initial impact. An emergent feature of our data is that *persistent disruptors* have driven substantial increases in planetary habitability (functional and taxonomic biodiversity, biomass, productivity, and resilience) over Earth history (figure 3) by reconfiguring biosphere structure and function over tens to hundreds of millions of years. However, *persistent disruptors* do not necessarily increase planetary habitability. This is illustrated by the Gaian bottleneck hypothesis in which life fails to persist on most planets where conditions are initially suitable for life to originate because planetary conditions move outside of the habitable range faster than life can evolve Gaian regulation to maintain habitability (e.g. through runaway greenhouse or icehouse climate states) [29]. In this case, the runaway climate state would be a *persistent disruptor*, locking in an undesirable biosphere state [27] of low (or no) biodiversity, productivity, and biomass [29]. Although *persistent disruptors* in Earth history have tended to increase planetary habitability (figure 3), it is possible that humans could become a *persistent* but degradational disruptor of Earth's biosphere.

Uniquely as an agent of change in Earth's history, humans have the *capacity to reflect on, govern, and potentially consciously modify our impacts* on the Earth System. Are we necessarily a *transient disruptor* of the biosphere, causing significant but ultimately short-lived losses of functional and taxonomic biodiversity and biomass, akin to past mass extinction events (e.g. [30])? Or do we have the potential to become a *persistent disruptor*, facilitating a transformation of the biosphere into a new configuration [31] that drives sustained enhancement of planetary habitability over longer time scales, ushering in a more productive and diverse biosphere state, as did the Cretaceous angiosperm revolution (e.g. [32])?

2. Ancient comparators for human activity

There are no analogues of past disruptors directly comparable to contemporary biosphere change. This is partly due to the rapidity of anthropogenic changes – of all the past disruptors we have identified, only the Cretaceous-Palaeogene (K-Pg) asteroid impact is likely to have had its maximum impact over a shorter timescale than humans (figure 2; e.g. [33,34]). It is also partly because of the unique characteristics of the Earth System before and during each past interval of biosphere disruption. For example, elevated extinction intensity throughout the early Palaeozoic is linked to lower atmospheric and oceanic oxygen concentrations during this time [35]. Biosphere evolution also shapes the potential for step-change increases in biodiversity, productivity, and biomass over time. For instance, large vascular plants and forests only evolved in the Devonian, meaning that pre-Devonian biomass and ecospace was much smaller than it is today [36], and the colonisation of terrestrial habitats allowed a shift towards the present-day state in which most global biomass is captured on land in trees [37].

Nevertheless, the *degree* of contemporary biosphere change can be compared to changes in deep time. For 30 intervals of macroevolutionary change in the fossil record (tables S3, S5), we evaluate the duration (figure 2), magnitude (figure 3), and rate (figure 5) of biosphere change. Where possible, we also consider the proximate cause (i.e., the disrupting agent) for each episode. We then evaluate the degree of anthropogenic biosphere disruption (a) so far, (b) likely to be caused by 2100 CE, and (c) potentially caused by 3100 CE; i.e., in the recent past and on near-future human timescales. We consider percentage changes, where possible, in species and genus richness, biomass, and productivity across each disruption interval as reported in the palaeontological and geological literature (table S5). To facilitate comparison with the literature on current, anthropogenic, biosphere change, we convert estimated species (or genus) extinction or origination rates typically expressed as percentage change in the palaeontological literature to extinctions or originations (E or O) per million species (genus) years (MSY [MGY]) following equation (1).

$$change/MSY = \frac{(taxonomic\ \%\ change) * 10^4}{interval\ duration\ in\ years} \tag{1}$$

We also make explicit comparisons between anthropogenic biosphere change and the loss of ecospace resulting from elevated global temperatures, deforestation, and the spread of ocean anoxia in the Permian-Triassic mass extinction (PTME; figure 1), as well as drawing comparisons with other intervals of disruption throughout Earth history in which the biosphere was either ultimately enhanced or degraded. We find that humans are acting faster than almost all past transient biosphere disruptors (figure 2) and with comparable magnitude (figure 3). Humans also have the potential to deliver the greatest rates of positive or negative change on the biosphere of all past disruptors, except for the K-Pg asteroid impact (figures 4 and 5).

(a) Transient disruptors

The fossil record reveals many intervals of Earth history in which *transient disruptors* acted on the biosphere on timescales ranging from seconds, years, and decades (e.g., the K-Pg boundary asteroid impact) to hundreds of thousands and millions of years (e.g., environmental change resulting from solid Earth processes; table S1; figure 2) [38,39]. *Transient disruptors* are geologically short-lived (tables S1, S3-S4, figure 2), with the disrupting force dissipating over time, even if the disruption caused to the biosphere continues long afterwards. In our dataset, *transient disruptors* have a mean duration of 8.0×10^5 years (standard deviation 8.8×10^5 years; median 5.0×10^5 years; n = 25; tables S1, S3-S4).

Transient disruptors are generally abiotic, deriving from forces beyond the biosphere, including solid Earth processes like major volcanic eruptions and extra-terrestrial disturbances involving bolide impacts (table S1). Although many solid Earth processes operate over very long timescales (10^7 to 10^8 years), they also express as shorter duration pulses (10^4 to 10^6 years) that can be experienced as critical moments or tipping points in abiotic environmental systems that cascade through the biosphere (e.g. [39,40]). Volcanic outgassing occurs over tens of millions of years, but large igneous provinces (LIPs) can develop more rapidly as the result of mantle plumes, delivering enormous volumes of climate-altering gases and aerosols into the atmosphere on much shorter timescales (often <2×10^6 years) with much of the outgassing taking place in even shorter pulses (10^4 to 10^6 years) [41,42]. Tectonic plates also move slowly, changing the face of planet Earth on timescales of 10^7 to 10^9 years, but there are key intervals in plate tectonic evolution that are experienced by the climate system and the biosphere as critical moments on shorter timescales (10^6 to 10^7 years) when changes in plate positions cause effective separation or connection of land masses and oceans. At the Eocene-Oligocene boundary (~34 Ma), for example, the separation of Antarctica from the South American and Australian continental plates and the deepening of the Drake Passage and Tasman Gateway facilitated thermal isolation of Antarctica, ice sheet growth, and global cooling that had a pronounced impact on the biosphere ([42] and references therein). Changing continental configurations can also trigger substantial regional changes in biodiversity (e.g., in the Pliocene phase of the Great American Biotic Interchange [43]), but because these are not global-scale biosphere disruptions we do not include them in our compilation here. More rarely, climatically driven changes influenced by the biosphere itself may have driven extinctions, such as with the Devonian expansion of land plants [44], though the relative impact is debated [45].

Transient disruptors in Earth history have typically degraded the biosphere (figure 3), with (mass) extinctions resulting in significant biodiversity and biomass loss driven by kill mechanisms that include hypoxia, rapid temperature change (typically heating) and coupled climate impacts such as aridity, and excess CO_2 (hypercapnia + acidification in the oceans + acid rain on land) [46–48]. For example, marine biomass declined significantly in the Late Devonian Kellwasser (Fr-Fm), Permian-Triassic (PTME) and end-Triassic (ETME) mass extinctions and possibly also in the Late Ordovician (LOME) and Cretaceous-Palaeogene (K-Pg) mass extinction events (tables S1 and S5) [49]. Biodiversity loss peaked in the PTME [46]. Terrestrial forests, and by implication net primary productivity on land, also suffered significant declines during the PTME [50] and ETME [51].

Transient disruptors generally result in much lower biodiversity, simpler trophic structures [28,52], and much reduced biomass [49,50] (figure 3). The biosphere then enters survival and recovery phases, often lasting many millions of years, during which further extinctions might occur (e.g. [28]) before a new biodiverse biosphere with a complex trophic structure re-evolves in the absence of the *transient disruptor*. Although the re-emerged biosphere may ultimately become more diverse than the one that went extinct, this happens once the effects of the disruptor have left the Earth System, e.g., after the bolide impact (K-Pg) or when atmospheric CO_2 levels fall as volcanic outgassing reduces (PTME, ETME).

Deforestation was widespread during the PTME, particularly at low latitudes [50], and was probably caused by a combination of global warming, aridity, and acid rain [47]. Net primary productivity on land was estimated to be ~70% lower in the earliest Triassic (~13.0 to 19.7 Pg C/yr) compared to the latest Permian (~54.4 to 62.5 Pg C/yr) [50]. This loss of primary productivity, as well as the considerable loss of genetic and functional diversity [28,53], clearly threatened the planetary boundary of biosphere integrity in the PTME, just as biosphere integrity today is threatened by loss of genetic diversity and human appropriation of primary productivity (figure 1)

[3]. By comparison, about one-third of global forest area has been lost since the Middle Holocene, with half of that loss occurring since 1900 CE [54] and the most recent losses focused on the tropics [55]. Deforestation since the Middle Holocene represents several hundred Pg C [36], with global forest biomass probably about half of its Early Holocene value [37]. Human appropriation of terrestrial net primary productivity (HANPP) is estimated at ~30% (16.8 Pg C/yr) of the mean Holocene value [3]. Anthropogenic deforestation is currently approximately half that of the PTME, and it has been suggested that the loss of undocumented biodiversity in tropical forests may already have crossed the mass extinction threshold [56]. Moreover, documented losses particularly in mammal and bird populations serve as a warning of massive species-extinction-to-come if nothing is done to prevent this (The Living Planet Index).

Increased temperatures and expanded low-oxygen conditions (hypoxia or anoxia) in marine environments are a predominant feature of past biotic crises (table S1) [46,48]. Model simulations suggest that just the combined effects of ocean deoxygenation (~80%) and increased sea surface temperature (+10°C) can replicate ~50% of regional extinctions in the PTME [57]. Ocean hypoxia, in concert with other factors such as rapid warming, acidification, and hypercapnia, was a PTME kill mechanism [47] and is one that increasingly resembles the trajectory of the oceans in the Anthropocene epoch [57]. The role of marine hypoxia has not been accorded the same relevance in driving present biodiversity loss as the related patterns of climate change [58]. Contemporary ocean deoxygenation is linked to increasing temperature, with an estimated 2% of the open ocean's oxygen lost since 1960 [59], 3 to 4% loss predicted by 2100, and potential widespread marine oxygen deficiency within a millennium ([58] and references therein). In coastal areas hypoxia correlates with those regions of the Earth where the human footprint is strongest (e.g., South and East Asia, the Gulf of Mexico, and Europe), linked to excessive nutrient flux and eutrophication [60,61]. In some near-future scenarios where global warming (relative to the 1850–1900 average) reaches ~4.9 ± 1.4°C by 2100, and ~10 to 18°C by 2300, the combined effects of warming and oxygen depletion could result in a mass extinction approaching the magnitude of major events in the Earth's past, though limiting global warming to ~2°C could reduce this risk by 70% [62]. Ocean temperature and ocean oxygen concentration are not independent of each other. Increasing ocean temperature reduces oxygen solubility (e.g. [59]), and there is both empirical and theoretical evidence that a large increase in ocean temperature can disrupt phytoplankton photosynthesis [63–65] and therefore disrupt the global oxygen cycle.

Declining ocean oxygen concentration is considered as a possible tipping element of global climate [66], and a sufficiently large decrease in the amount of dissolved oxygen can potentially lead to a tipping cascade in the whole Earth System [67]. However, ocean oxygen concentration is not explicitly included in the planetary boundaries scheme of contemporary change, and instead the phosphorus control variable is used as a proxy for the risk of ocean anoxia [2,3]. Ocean oxygen concentration is simpler to estimate in deep time than is ocean phosphorus concentration, and oxygen dissolved in the ocean has been persistently and measurably declining since at least 1960 [59,60]. Given the current trajectory of ocean oxygenation [58–60] and the strong association between major biotic crises and low ocean oxygen concentrations in deep time (table S1) [46,48], we reinforce the suggestion of [68] that ocean oxygen concentration should be included explicitly in the planetary boundaries framework.

(b) Persistent disruptors

The fossil record also reveals many intervals of Earth history in which *persistent disruptors* acted on the biosphere on multi-million-year timescales (figure 2, tables S2-S4). In our dataset, *persistent disruptors* have an arithmetic mean duration of ~1.6×10^8 years (standard deviation ~1.7×10^8 years, median ~7.5×10^7 years; n = 5; tables S3-S4). In contrast to the *transient disruptors* that we review above, *persistent disruptors* remain in the Earth System long after they first appear and long after their initial impact. Here, we consider their duration as the interval over which their initial impact was greatest (range of best-estimate durations: 4.0×10^7 to 5.0×10^8 years). *Persistent disruptors* in Earth history typically promote greater planetary habitability by supporting greater taxonomic and functional biodiversity, productivity, and biomass (figure 3) including through providing new symbioses and interactions, even if they initially cause harm to the incumbent biosphere. Persistence is not in itself desirable, and biologically impoverished (undesirable) system states can be resilient [27], but the *persistent disruptors* that we have identified in the geological record have all driven substantial increases in planetary habitability across different metrics (figure 3). *Persistent disruptors* primarily originate from within the biosphere itself (table S2), rather than from solid Earth processes as do *transient disruptors*. In this context, anthropogenic impacts on the biosphere originate from within the biosphere itself. Here we focus on two *persistent disruptors* in Earth history that resulted in greater biosphere productivity and diversity: the evolution of oxygenic photosynthesis during the Great Oxygenation Episode (GOE), and the terrestrialization of the biosphere.

The evolution of oxygenic photosynthesis is one of the earliest *persistent disruptors* to leave a clear signal in the geological record, known as the GOE which began ~2400 Ma and lasted ~200 to 300 million years [38 and references therein, 69]. Oxygenic photosynthesis in the microbial biosphere liberated free oxygen into the atmosphere and oceans, causing the oxygenation of Earth’s surface environments and facilitating the subsequent diversity of more complex organisms, including eukaryotes, with higher energy demands satisfied by the greater energy released by oxidative phosphorylation [70]. However, the GOE caused significant disruption to the pre-existing biosphere that was largely adapted to oxygen-poor environments and predicated on anaerobic processes of respiration [71]. Primary productivity increased during the GOE, possibly exceeding modern levels, before falling back to a lower level for most of the Proterozoic [72]. Subsequent increases in atmospheric and oceanic oxygen concentrations from the rise of photosynthetic eukaryotes in the Mesoproterozoic and land plants in the Phanerozoic both further elevated primary productivity [72].

The evolution of land plants and the development of a terrestrial biosphere from ~475 Ma [73] also proved to be a *persistent disruptor* of the biosphere, involving complex interactions between plants and fungi [74] seen in some of the earliest fossilised terrestrial ecosystems [75]. These interactions provided fungi with carbohydrates from the plants, whilst in return the fungi greatly extended the soil volume from which plants could extract nutrients [76]. Invertebrate and vertebrate animals then became key parts of these ecosystems from the Silurian and Devonian (e.g. [77,78]). Symbiotic relationships were critical in the later diversification of angiosperm plants from the Cretaceous onwards [32]. In the early stages of biosphere terrestrialization, land plants changed the Earth System by increasing atmospheric oxygen levels [79] and may have contributed to global cooling in the Late Ordovician by removing CO_2 from the atmosphere [80]. The plant biosphere developed large trees and forests from the Middle Devonian onwards [81] that has ultimately resulted in most biomass being concentrated on land (e.g. [37]), with an upper ceiling at around 980 Pg C above which interactions between a more oxygenated atmosphere and forest fires act to limit additional plant growth [36,82].

Embedded within the evolution of the terrestrial biosphere is the further *persistent disruptor* of the angiosperm (flowering plant) revolution in the late Mesozoic and early Cenozoic, which drove terrestrial biodiversity and biomass to exceed its marine counterpart (table S2) [32,83]. The modern terrestrial realm hosts ~85 to 95% of total macroscopic species diversity on Earth [83]. The plant-dominated terrestrial biomass at 470 Pg C is almost two orders of magnitude greater than the marine biomass at 6 Pg C, even though primary production (measured in produced mass of carbon per unit time) is similar in the oceans and on land, with a much greater turnover in the marine realm [37]. Angiosperms are the dominant component of terrestrial biomass, being much more productive than gymnosperms [32], and the rise of angiosperms probably drove the decline in conifer diversity and their concomitant increased extinction risk [84]. Angiosperms evolved a huge range of mutualistic relationships with fungi and animals, especially insects, and enhanced the habitability of terrestrial tropical wet biomes, providing a much greater range of interactions and environments for insects and other animals [32]. Cascade effects from the angiosperm revolution include the diversification of spiders, notably ground hunters of insects, of amphibians that live in humid tropical forests, and of mammals and birds that fed on the insects associated with, or fruits produced by, these plants [32]. In this way, the angiosperm radiation enabled the evolution of entire ecosystems that were simply impossible before their arrival and enhanced planetary habitability even whilst the incumbent conifer ecosystems declined and shifted into higher latitude, higher elevation, and lower productivity parts of the terrestrial realm.

3. Do some patterns of human interaction with the biosphere resemble persistent disruption?

Both *transient* and *persistent disruptors* permanently reshape the biosphere. *Transient disruptors* can clear out biodiversity and break down existing trophic structures through (mass) extinctions, thereby indirectly facilitating the permanent reshaping of the biosphere through the eventual evolution of new species and ecosystems. *Persistent disruptors* can reconfigure the state of the biosphere by promoting productivity, enhancing symbioses and mutualisms between species and facilitating the evolution of new species and ecosystems. The question is, will humanity's permanent reshaping of the biosphere (e.g. [85]) result from us acting as a *transient disruptor*, to be followed by a long interval during which low functional and taxonomic diversity is locked into the global ecosystem? Or can we identify pathways by which humanity can be transformative of the biosphere, as a *persistent disruptor* that enhances global biodiversity? The latter scenario would seek to emulate the 'Green Road' shared socio-economic pathway SSP1 of greater equality, human well-being, lower overall growth and consumption, and greater sustainability [86]. However, if following the path of a *transient disruptor*, human activity would run closer to the 'Rocky Road' SSP3 or 'Highway' SSP5 scenarios in which global environmental degradation is high, even if technology and conservation efforts prove effective locally (SSP5) [86]. Here we attempt to plot humans as both *transient* (business as usual) and *persistent disruptors* (sustainable stewardship: a more desirable social-ecological reorganisation) in figures 3 and 5 (tables S3 and S5) and highlight three interrelated pathways towards the latter type of disruptor that can encourage a more biodiverse- and biomass-rich wild biosphere.

(a) Fostering more diverse human influenced ecologies

Persistent disruptors have increased the range of habitats available to life and thereby fostered more complex and diverse ecosystems (table S5). Human practices have been shown to replicate this by leveraging local knowledge and community-based approaches to landscapes that develop and support new symbioses and consequently increase biodiversity.

Many social-ecological systems support both human and nonhuman species around the world [20]. Indigenous communities around the North Pacific rim have maintained sustainable salmon fisheries for thousands of years and enabled intensive long-term use of this fish as a food resource by emphasising mutualism and multi-generational sustainability rather than maximising short-term exploitation, for instance through the use of technologies to harvest fish without negatively impacting nontarget species [23].

Human-landscape co-evolution over the last ~50 kyr has resulted in enhanced biodiversity in the western Australian desert through processes of patch-mosaic burning that increased the number of ecological niches and reduced the risk of very large destructive fires (e.g. [22,87]). Burn-back of spinifex grassland in the winter months increases the ecological space for a range of other plants, such as bush tomatoes [87], and the greater diversity of plants helps support a more diverse and abundant community of lizards and mammals (e.g. [12,88]). Patch-mosaic burning processes were developed by the Indigenous peoples of Australia to improve foraging and hunting outcomes over many millennia [87]. Increased biodiversity and population sizes are an emergent property of this practice, which is rooted in societal values of social and environmental sustainability and demonstrates that humans can act as biodiversity-enhancing ecosystem engineers on multi-millennial timescales [87]. Similarly, in the Mediterranean region, multi-millennial cork-oak savannahs support biodiverse mammal-, bird-, shrub- and grassland ecologies [20] that have resulted from forest clearance, including by fire and livestock grazing.

Traditional ecosystem management practices in which humans have improved local biodiversity and habitat heterogeneity have sometimes been threatened by government policies that shifted people off the land [12], or encouraged reforestation through agri-environmental schemes, or via economic reasons leading to land abandonment [20]. Return of land to Indigenous stewardship [22] and new active attempts to increase heterogeneity have sometimes been shown to correlate with increased biodiversity, with the greatest biodiversity and biomass gains found from moderate areas and frequencies of patch burns [89].

In monocultural industrial farming, ecological structure and diversity is much reduced. However, in many agricultural landscapes, both the range of crop types and the arrangement of those crops may increase wild biodiversity. Small-scale heterogeneity (e.g., within individual farms or even within fields in the case of regenerative agriculture and agroforestry) is able to support greater invertebrate biodiversity, with larger scales needed to support enhanced vertebrate richness [90]. There is no one-size-fits-all approach, and a range of heterogeneities is needed to optimally support enhanced biodiversity [90], possibly with peak diversity achieved with a medium degree of heterogeneity (e.g. [91]).

Matrix farming approaches intercalate areas of least impacted natural biosphere with a mixture of farmland uses that promotes biodiversity, species movement, and species interaction [21]. Such ‘working lands’ support local human communities whilst also allowing elements of the wild biosphere to move across the landscape by emphasising multifunctionality rather than maximising the production of one particular animal or crop [21]. Conserving biodiversity in working landscapes will be essential to supporting wildlife in protected areas too, where those areas alone may be insufficiently large to preserve biodiversity, especially as climate changes rapidly [21].

(b) Sparing and sharing, land and sea

Past *persistent disruptors* have improved the production, capture, and recycling of biomass, and thus provided a sustained increase in energy available to the biosphere (table S5). Humans are capable of massively increasing biomass in components of the Earth System. Humans have increased total mammal biomass approximately threefold since 1850, but this increase is due to higher numbers and greater weights of domesticated livestock, and wild mammal biomass has approximately halved over the same time [18]. The human appropriation of mammal biomass and the primary productivity needed to sustain it has contributed to humanity driving the biosphere beyond its safe operating limits (figure 1) [1,3].

In the debate about land use policies in the 21st century, conservationists have identified two major pathways to restoring biodiversity: ‘land sparing’ by establishing separate land areas for intensive agriculture and conservation [92]; and ‘land sharing’ by developing multifunctional land use [93] where agricultural, nature restoration, and climate objectives are pursued on the same land. The increase in agricultural production in the 20th century has led some to suggest that humans are near peak agriculture [94] and can begin to yield land back to wildlife [95]. Regionally this pattern is complex, with some areas still experiencing agricultural expansion ([96] and references therein). Nevertheless, humanity may be able to enter a phase of intensification rather than extensification of land use [96] in which human impacts shift from degrading to enhancing the biosphere. This may involve a combination of more diverse farming methods using, for example, crops that are resilient to climate change [97], a greater diversity of plants [98], and practices that bring together ecological intensification and agro-ecological farming [15]. Intensification may come from the use of new technologies including vertical farming systems which can increase agricultural productivity and reduce demand for land [99], by increasing the photosynthetic efficiency of plants, especially those using C4 photosynthetic pathways including maize, sugarcane, and sorghum [100], and through the development of perennial varieties of crops including wheat, rice, and sorghum. Other agricultural innovations can improve and better maintain soil health and productivity, such as extending the symbioses between bacteria and plants to enhance nitrogen fixation [101]. In this new phase, land currently given over to agriculture could be spared where suitable and sustained management could help biodiversity recovery alongside carbon capture [96].

However, the challenges here are manifold. Although some regions may be approaching peak agriculture, the world needs to increase food production by at least 50% to feed the projected

9.8 billion people by 2050, with demand for animal-based food rising by 70% [102]. Pivoting to vegetarian and vegan diets would help because animal-derived protein uses five to ten times more water than growing vegetables [103]. If global reliance on animal-based foods declined from 20% to 5%, everyone could enjoy adequate nutrition while avoiding water deficits [104]. Labour constraints in the agrarian sector present a challenge to adapting farming practices towards systems that support higher biodiversity, and government subsidies may be required to make farming profitable while intensifying operations [105]. Climate change is reducing agricultural productivity of both calories and nutrients. With every degree of global warming, calorie production of staple crops per person per day declines by ~120 kilocalories (~4% recommended daily amount) [106]. Even accounting for adaptation measures (currently more widespread in relatively low income, hot regions of the world), the impact of rising temperatures on the production of soybeans, wheat, maize, cassava, sorghum, and rice remains negative and meaningful [106]. If net zero carbon emissions can be reached quickly, global crop yields will decline by 11%, but if emissions rise unchecked, the decline is 24% [107]. Measured not in terms of calories but in terms of the seven food groups necessary for a healthy diet, the only self-sufficient country in the world is Guyana [108]. More than one-third of all nations achieve self-sufficiency in only two or fewer of these seven food groups, making them particularly vulnerable to supply chain disruptions [108]. Currently, more than two billion people suffer from malnutrition due to micronutrient insufficiency, especially iodine, iron, folate, vitamin A, and zinc [109]. Water and changing climates are serious limitations for agricultural innovations globally. Managing the land with the twin goals of supplying adequate nutrition for people and bolstering biodiversity can be accomplished through a careful balance between physical and social constraints once the challenge is framed as transitioning to being persistent disruptors and stewards of the land.

Biodiversity does not automatically recover following land abandonment in many landscapes (e.g. [110]), and these landscapes will need considerable input from humans for their restoration. A targeted approach to ecosystem restoration could help to reduce further biodiversity loss, whilst also sequestering hundreds of gigatons of carbon dioxide [111]. Approaches towards ecosystem management and nature restoration, including rewilding [112–116] clearly speak to this theme, as do policy measures to halt and reverse biodiversity decline (e.g. [117]). Many such interventions create co-benefits between climate mitigation from low-emission land use systems and nature recovery targets [118]. As discussed above, humans have the potential to be positive forces of ecosystem engineering and biosphere enhancement where they maintain a persistent presence in landscapes and focus on long-term, multi-generational, sustainability.

Just as terrestrial systems are moving into a phase where deliberate human stewardship can begin to reverse past degradation and enhance biosphere functioning, the marine realm exhibits an opportunity for a parallel challenge. Similar dynamics that have reconfigured landscapes have also reshaped seascapes: accelerating pressures, expanding human uses, and widening ecological imbalances. Yet, as on land, a combination of scientific understanding, innovative management approaches, and increasingly coherent international governance suggests that oceans, too, could be entering a period in which human intervention can shift from being primarily extractive to becoming restorative and regenerative. Building on this symmetry between terrestrial and marine trajectories, we here consider how current ocean governance, ecological tools, and legal frameworks can support a comparable transition toward biosphere enhancement at sea.

As with terrestrial ecosystems, the oceans reveal both the scale of human disruption and the scope for regenerative intervention. Although less than 10% of the global ocean is currently designated as a Marine Protected Area (MPA), and many marine ecoregions still have under 1% protection [119,120], recent governance developments suggest transformative expansion towards effective protection. Historically, targeted international interventions have demonstrated that marine ecosystems can rebound when coherent rules are applied. The 1911 North Pacific Fur Seal Treaty curtailed pelagic sealing, and later interwar bans on right whale hunting helped limit further depletion of vulnerable species [120]. These were precursors to the modern legal architecture: the 1982 United Nations Convention on the Law of the Sea (UNCLOS) [121], which establishes global duties to protect and preserve the marine environment, and the 1995 Fish Stocks Agreement (entered into force on 11th December 2001) [122], which operationalizes precautionary and ecosystem-based approaches for straddling and highly migratory species.

Building on these foundations, the 2023 High Seas Biodiversity Treaty (BBNJ Agreement, entered into force on 17th January 2026) [123] enables the creation of area-based management tools, including high seas MPAs, supported by environmental impact assessments and capacity-building measures. Overall, the BBNJ Agreement provides, for the first time, a mechanism to ‘spare’ portions of the high seas through legally established protected areas, a global stewardship complementing national exclusive economic zone (EEZ)-level stewardship. However, sparing marine areas is practically more challenging than sparing land areas, as any boundaries put in place are more porous to deliberate and accidental incursion, for example as currents sweep pollution across the oceans. It is important, therefore, to accompany specific partial protection measures for the ocean with global approaches that consider the interconnectedness of the whole marine realm.

At the interface of ecology and governance, ecosystem-based management has become central to reconciling seafood production with biodiversity conservation. Regional fisheries management organizations (RFMOs) now integrate ecological considerations into bycatch mitigation, habitat protection, and harvest strategies, though significant gaps in implementation remain. In parallel, emerging dynamic ocean management tools – informed by satellite data, species distribution models, and real-time environmental indicators – demonstrate that it is possible to reduce impacts on nontarget species while maintaining or even improving fisheries performance.

Taken together, these developments suggest that the oceans, like terrestrial systems, may be entering a phase where human presence – guided by coherent legal and policy frameworks, and supported by science-based management – can increase the adaptive capacity and long-term transformability of marine social-ecological systems. Achieving the Kunming–Montreal Global Biodiversity Framework's 30×30 target in the marine realm will require precisely this integration of spatial protection, effective governance, ecosystem-based management, and adaptive technological tools, in order to enable the recovery of marine biodiversity while sustaining the food systems upon which billions (humans and non-humans alike) depend.

To succeed in a transition of humans from a *transient* to *persistent* disruptor concerning the marine biosphere, a profound change in policy and legal approach will be necessary: from the prevalent 'freedom of the seas' approach [121,124] and the 'common heritage of mankind' approach ([121] Part XI) to the 'responsibility for the seas' approach [125,126]. This means a transition in our approach to ocean governance, from an extractive focus, characterising both the 'freedom of the seas' and 'common heritage of mankind' principles to a stewardship and protective approach (e.g. [127]). This shift – from primarily extractive to essentially regenerative marine governance – illustrates how humans might move from acting as a *transient disruptor* of ocean systems to becoming *persistent* agents of enhanced planetary habitability, through stewardship, adaptive governance, and potentially transformation towards more desirable marine regimes.

This transition should not be expected to be led by moral or idealistic reasoning; rather it will be born out of necessity. The Earth System, for long implicitly considered a stable background for economic and political development of human societies through the Holocene, is increasingly understood (in the Anthropocene epoch) as simultaneously vulnerable to disruption from overwhelming human impacts and the precondition for human future. Once this realisation is translated into political, economic/financial, and legal change of human (via states') activity, humans may enshrine the prospects of evolving from a *transient* to a *persistent* disruptor. In this sense, ocean governance becomes a critical arena in which the broader transformation toward 'common responsibility for the Earth System' [128] must unfold.

(c) Novel ecologies and associations of species

Land abandonment facilitates the emergence of novel ecologies that evolve after human activity has ceased. In one sense these communities might resemble recovery faunas/floras like those that follow the extinctions precipitated by *transient disruptors* in deep time (e.g. [28]). However, near-future recovery faunas/floras would be uniquely different from those in deep time because they will comprise a community with a revised, more globally homogeneous, complement of species through non-native translocations [129]. In terrestrial settings, novel ecosystems are now typified by non-native species [130]. In many marine/oceanic settings, such as coral reefs, non-native species currently play a smaller but growing role (especially on islands), and novel ecologies are characterised by range shifts and the unequal responses of species to environmental change [131]. Nevertheless, in some coastal marine ecologies, the complement of species has been radically changed by species translocation [132,133], leading to the emergence of ecosystems with very different compositions (e.g. San Francisco Estuary [134]). The translocation of non-native species is one of the major causes of biodiversity loss in ecosystems across the world (e.g. [135–138]). However, many non-native species merge into the native ecological community without negative effects [139]. Therefore, in some cases the arrival of non-native species can enrich the ecosystem rather than degrade it (e.g., the UK's floral diversity has been approximately doubled by species introductions [140]).

Although species extinction and reduced populations of wild species at the global level are now serious problems [30,141], 'novel' associations of species at the local and regional level (e.g., in urban areas or abandoned agricultural land) provide homes to new or previously rare species [142]. The common house mosquito in the UK invaded the London Underground system and evolved to become a different species, no longer able to breed with its above-ground progenitor [143]. Processes of species translocation, agriculture and horticulture lead to more rapid hybridization and speciation, often within a few generations [25,144–146]. Hybridisation is not well studied for marine ecologies, but examples include those between the Mediterranean mussel *Mytilus galloprovincialis* and the Pacific *Mytilus trossulus* [147]. In the terrestrial realm, Thomas [25] noted ~6 to 8 new hybrid species of cultivated crops resulted from human intervention. Thomas [25] also noted that most new agricultural and horticultural species are obligate mutualists of humans, whilst many of the new species that have naturalised are facultative mutualists, and he suggested that land plant speciation rates may now be the highest in their evolutionary history. In co-opting humans to disperse their seeds, such patterns resemble the symbioses that formed between animals and flowering plants in the Cretaceous (table S2). However, most such plants probably occupy landscapes that are heavily impacted or designed by humans, and therefore represent only a small gain in a current biodiversity net loss, and species resulting from novel human ecologies should not be seen as a trade-off against the ones made extinct [143,148].

Humans deliberately and unconsciously produce waste materials in vast quantities, with increasing volumes of this waste being hard-to-degrade plastics [149]. This waste is harmful to the biosphere, with micro- and macro-plastic pollution being a significant problem for both environmental and human health. However, the biosphere itself may offer some hope for remediation, with both terrestrial [150,151] and marine [152] fungi and bacteria being able to break down many of the plastic-forming polymers. If new microbial ecologies can be fostered in areas of concentrated human-produced waste, there is potential both to support novel microbial communities and to reduce our environmental impacts with the support of the biosphere. A precedent in Earth's history would be the evolution of lignin decomposition in deep time, perhaps as early as the Late Devonian, which enabled the decay and recycling of woody tissues on land [153].

These novel assemblages, commonly with locally enhanced biodiversity, may become very significant as climate change, the continued translocation of non-native species, and widespread toxic pollutants increasingly impact local assemblages. Such novel assemblages may then serve, often inadvertently, as 'environing technologies' which shape landscapes and environments on micro, local, and planetary scales [154]. It may be that these assemblages emerge as the survivors within a progressively Anthropocene-influenced global environment [155].

4. Conclusions

Humans have the capacity to recognise, govern, and potentially transform their impacts on the Earth System, even though this capacity is uneven and contested. Humans sometimes emulate *persistent disruptors* of the biosphere from the Earth's deep past, those which led to enhanced biosphere productivity, biomass, biodiversity, and especially greater mutualisms and symbioses between species (table S2, figure 3). These *persistent disruptors* ultimately drove greater planetary habitability. Nevertheless, even if we accept that some novel and managed ecologies are emerging that might resemble the impact of a *persistent disruptor* it seems prudent to preserve the existing biodiversity around us, and not to threaten its integrity in ways that precipitate a crisis that resembles the impact of past *transient disruptors* [30], which is our current trajectory (figure 3). Earth history tells us that if we allow ourselves to be a *transient disruptor*, then the resulting mass extinctions lead to a depauperate biosphere for millions of years, with highly degraded ecosystems and much-reduced biomass and biodiversity. It also tells us that extinctions can be highly selective, with some ecological- and biological groups impacted significantly more than others (e.g. [156]). If we continue our current trajectory, humans will have had the second highest rate of negative impact on the biosphere in Earth history, after only the K-Pg asteroid impact (figure 5). However, we also have the potential to have the highest rate of positive impact on the biosphere in Earth history, and to do so on human timescales of decades to millennia (figure 5; table S5). For this to become possible, a profound change in the political and legal framework – towards a 'common responsibility for the Earth System' as a component of international law – is a prerequisite.

We wanted to show here that the geological and palaeontological record, often used as a comparison with contemporary biosphere decline, also reveals how the biosphere has enhanced its biomass and biodiversity over long timescales. Innovations from within the biosphere itself, such as atmospheric oxygenation in the GOE and the mutualisms forged by flowering plants (table S2), have driven sustained increases in biodiversity, productivity, and biomass over billions of years (figure 3). Humans have the potential to learn these lessons from Earth history, to become a transformative and *persistent disruptor* of the biosphere, and to ultimately enhance planetary habitability.

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Data and code availability

The code used to produce figure 1 is available on GitHub at: https://github.com/twwh01/planetary_boundaries_plots. The supplementary data and code necessary to reproduce all other figures and analyses are available on GitHub at: https://github.com/twwh01/disruptors.

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Figures and Tables

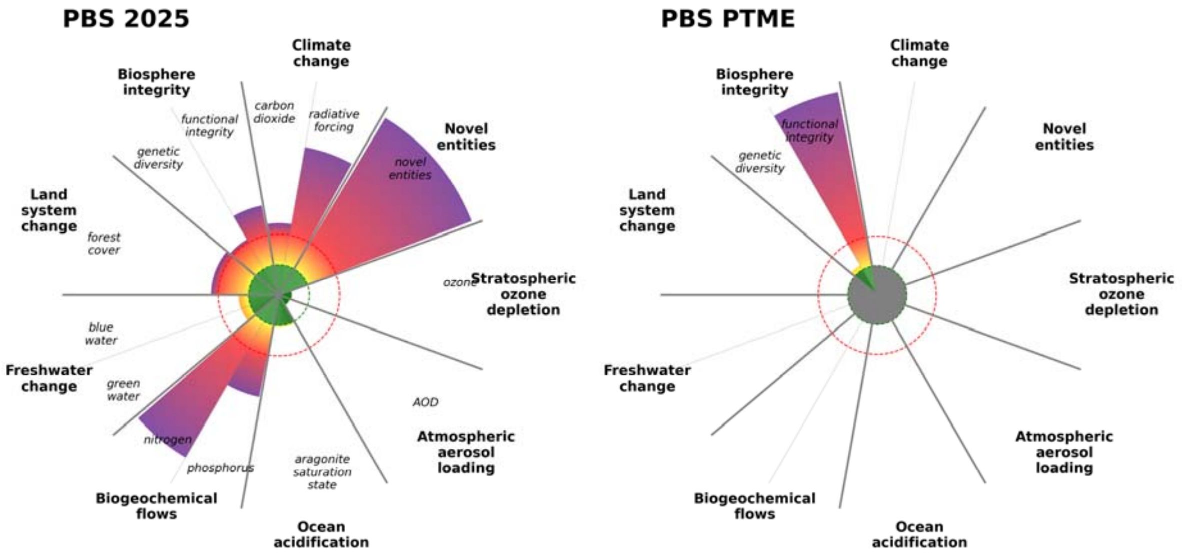


Figure 1. The planetary boundaries framework reveals that humans are pushing the Earth System beyond the safe limits of its recent past [1]. Planet Earth has been pushed beyond the safe operating space for its biosphere many times in the deep past, with these intervals often driving biotic crises and even mass extinctions. The modern planetary boundary values are shown on the left (PBS 2025; after [1]) next to estimates for the biosphere integrity boundary for the Permian-Triassic Mass Extinction ~252 million years ago (PBS PTME; see figures 2, 3). The PTME species extinction rate of ~95% equates to ~15 extinctions per million species years (following [157]: ~60 kyr duration estimate for the PTME; see also [30]). Green dashed line: threshold for safe operating space; red dashed line: boundary of the zone of increasing risk and the high-risk zone. We have deliberately not attempted to quantify other elements of the PTME planetary boundaries.

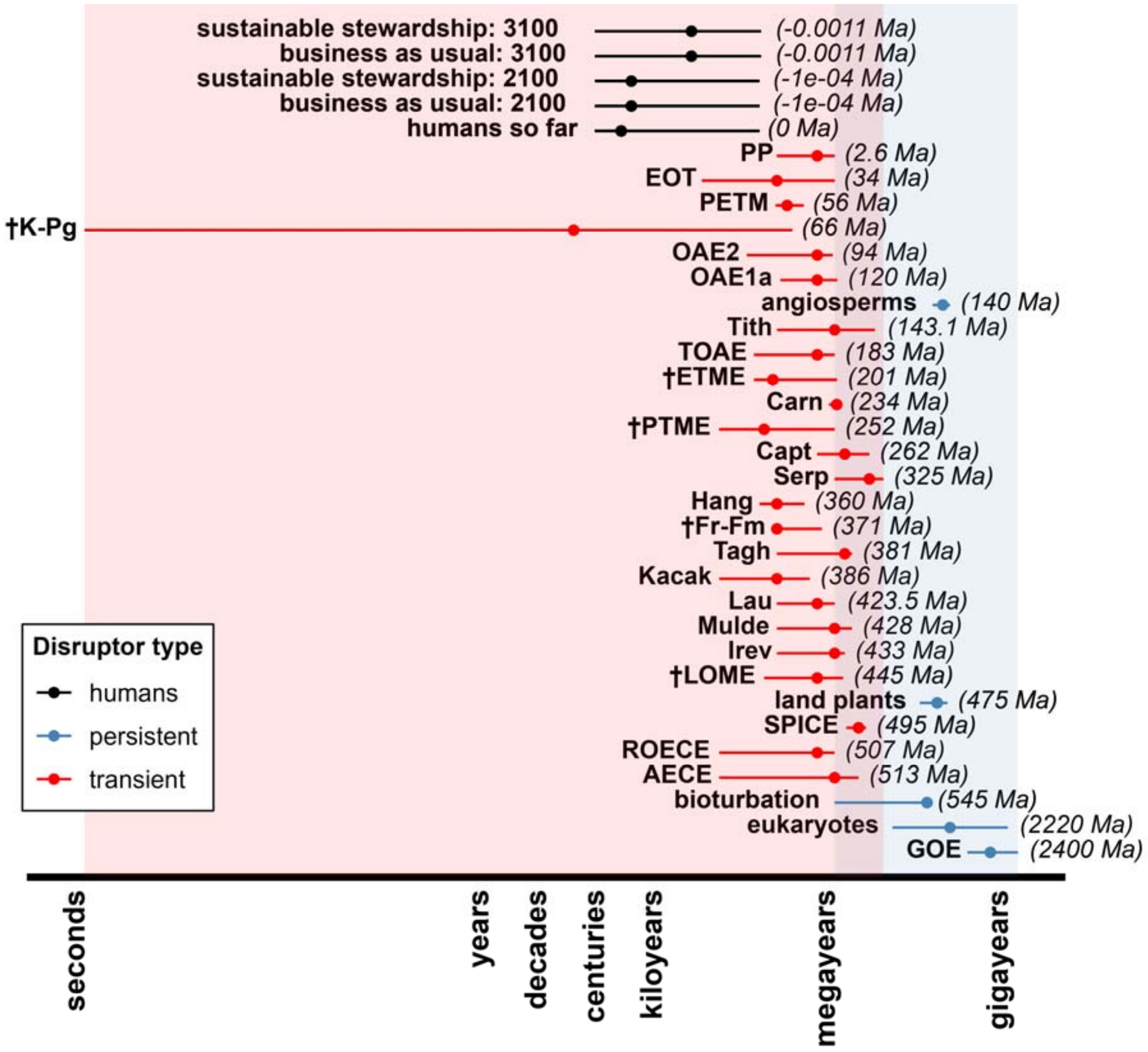


Figure 2. Timescales ($\log_{10}$) of *human disruption* (black) alongside *transient* (red) and *persistent* (blue) *disruptors* in Earth history, with the geologically oldest disruptors at the bottom and near-future disruptors at the top. Each line represents the range of timescales over which the disruptor acted or will act on the biosphere with each point indicating the main timescale of impact. Dagger-marks (†) indicate the 'Big 5' mass extinctions. The age of each disruption in millions of years ago (Ma) is in parentheses on the right of each line. See table S3 for data and abbreviations.

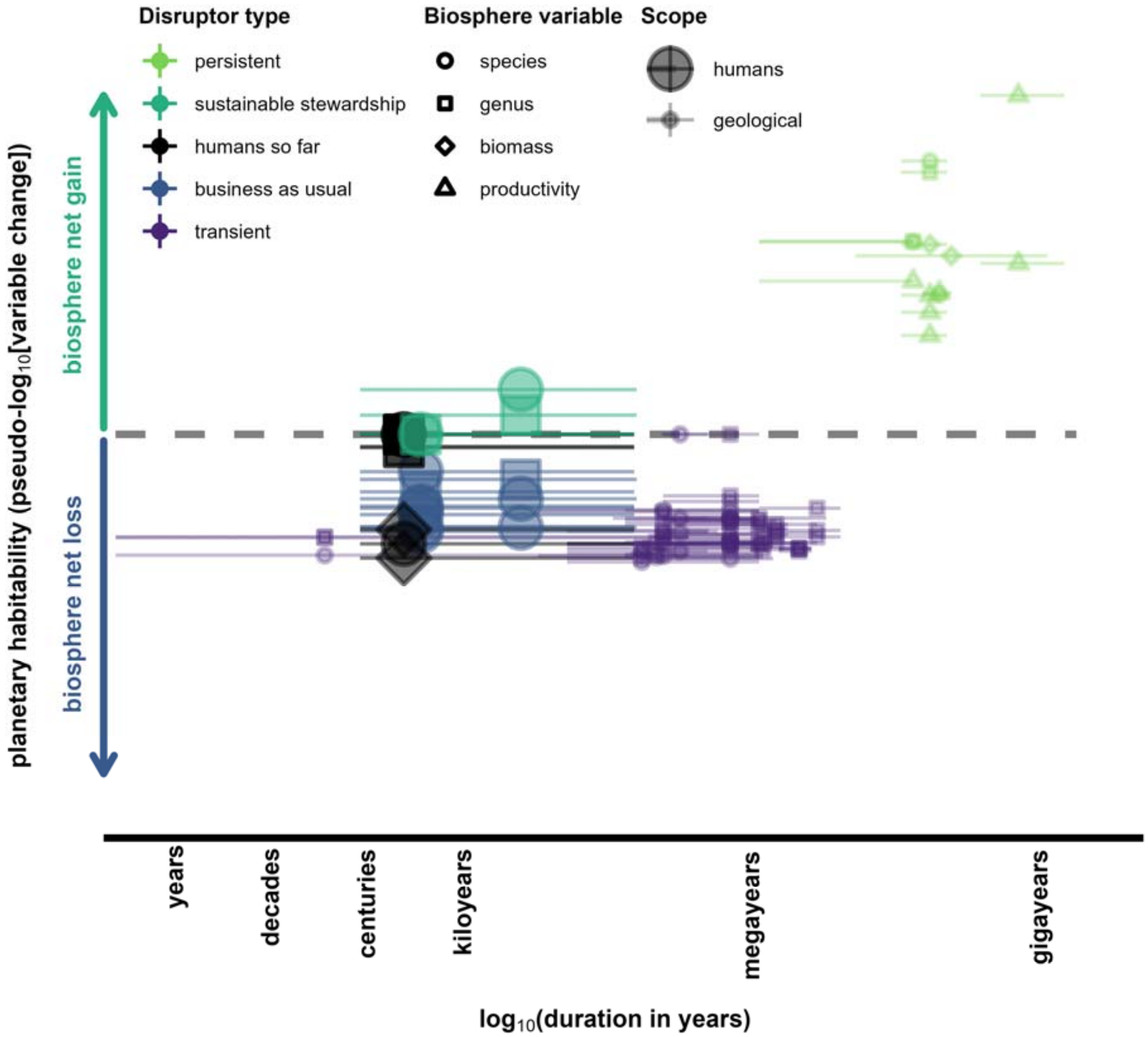


Figure 3. Timescales and calculated impacts of human disruption (large symbols) plotted alongside *transient* and *persistent disruptors* in Earth history (small symbols). *Persistent disruptors* from Earth history plot in the top right, operating on long timescales and driving biosphere net gain. *Humanity as a disruptor* plots with the past *transient disruptors* for current and business as usual future disruption, with short timescales and negative biosphere impacts, but humanity has the potential to drive biosphere net gain on short (century to millennial) timescales. Both axes are $\log_{10}$ scales with the x-axis in years and the y-axis in percentage change of biosphere variable (species richness, genus richness, biomass, and productivity). Each point is plotted at its central duration estimate with error bars representing its potential range of durations. See tables S3 and S5 for the data shown in this figure.

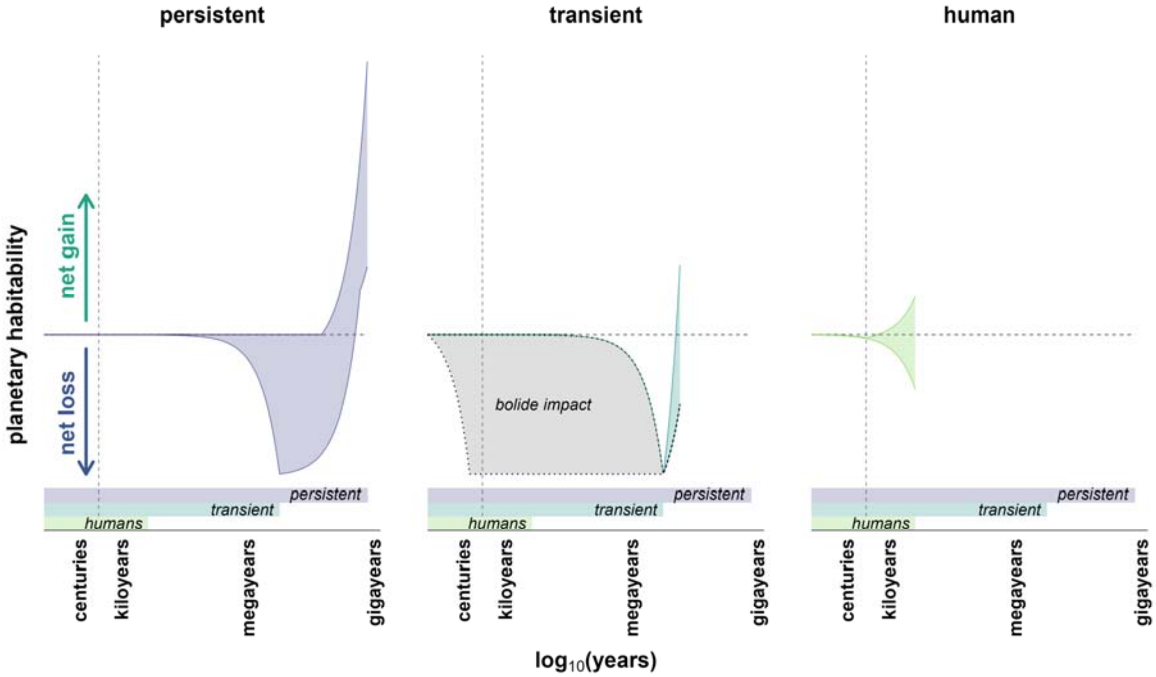


Figure 4. Schematic representation of the potential range of biosphere impacts (enhancement or degradation) from *persistent* and *transient disruptors* compared with anthropogenic (human) disruption. The scale of biosphere impact is consistent across panels and represents proportional loss/gain; the net gain and net loss arrows are of equal lengths; the horizontal dashed line represents no relative change. Bottom solid bars show the disruptor durations. The grey box indicates the time-biosphere impact area occupied by the transient disruption of a bolide impact, like that at the Cretaceous-Palaeogene (K-Pg) boundary. Vertical dashed line shows the timescale over which we consider humanity to have been a disruptor to-date (~200 years). *Persistent disruptors* may drive initial biosphere degradation before any overall biosphere enhancement over the duration of their impact. *Transient disruptors* drive biosphere degradation for the whole duration of their presence, with biosphere recovery or transformation taking place after the disruptor and its effects dissipate. Human activity has so far degraded the biosphere and may continue to do so; however, humanity has the capacity to potentially transform their impacts and ultimately enhance the biosphere even on millennial timescales.

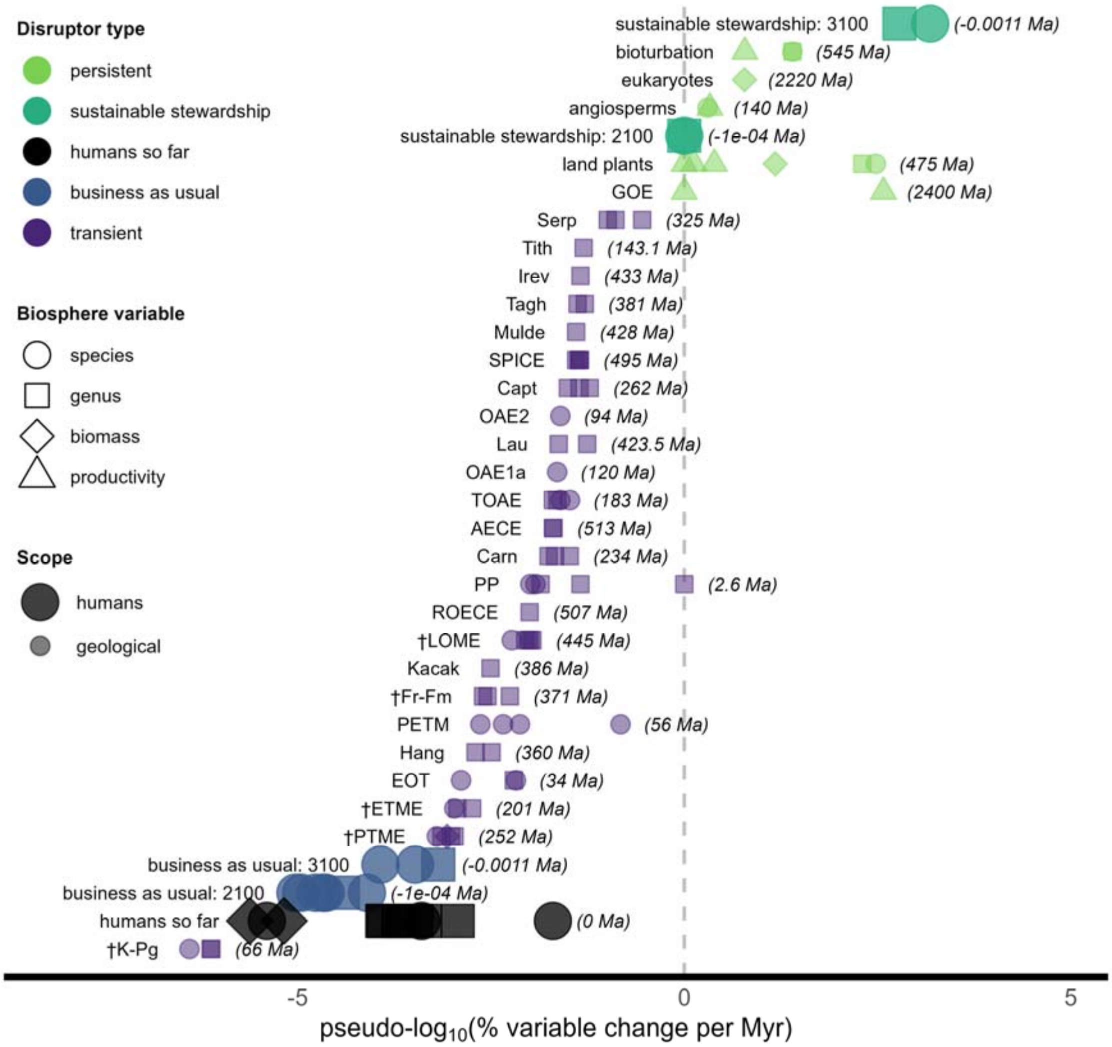


Figure 5. Humanity is driving the second highest rate of negative biosphere change in Earth history, after the K-Pg bolide impact, but we could become the greatest driver of positive biosphere change over the next millennium. This figure shows rates of *human-driven disruption* (large symbols) alongside *transient* and *persistent disruptors* in Earth history (small symbols), with the highest negative rates at the bottom and the highest positive rates at the top. Each point represents an estimate of biosphere variable change rate (% change per duration in Myr) on a pseudo-$\log_{10}$ scale: percentage changes smaller than ±1% are considered negligible and treated as zero; negative rates calculated as $-1*\log_{10}(|\%\ \text{change rate}|)$. Dagger-marks (†) indicate the 'Big 5' mass extinctions. The age of each disruption in millions of years ago (Ma) is in parentheses on the righthand side. We plot scenarios for impacts on the biosphere according to different future human trajectories. Data in tables S3 and S5.

Supplementary

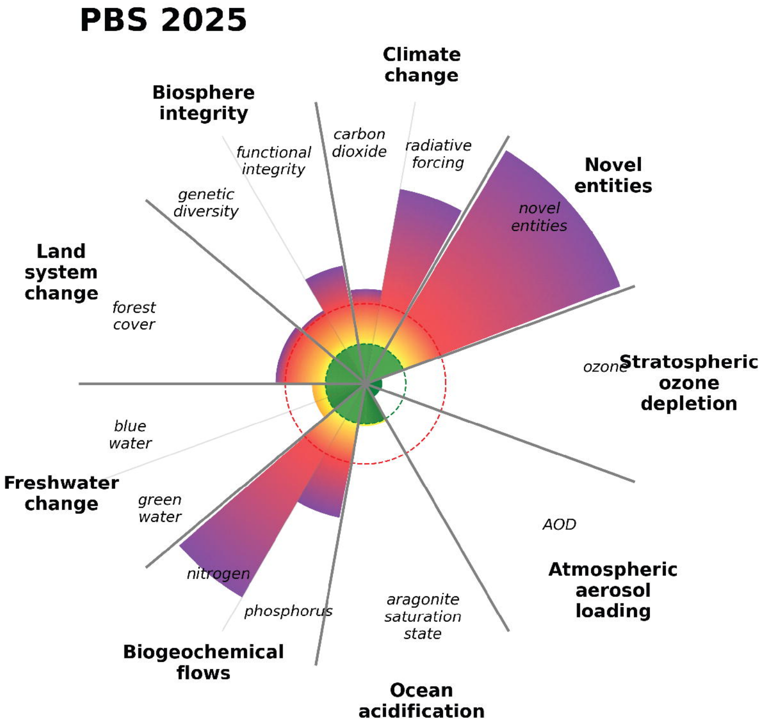
Table S1. Examples of transient disruptors from Earth's deep past to contemporary associated with substantial habitat loss caused, for example, by global changes in climate and low oxygen concentrations in the marine realm. Unless otherwise stated, data follow [46,48,158].

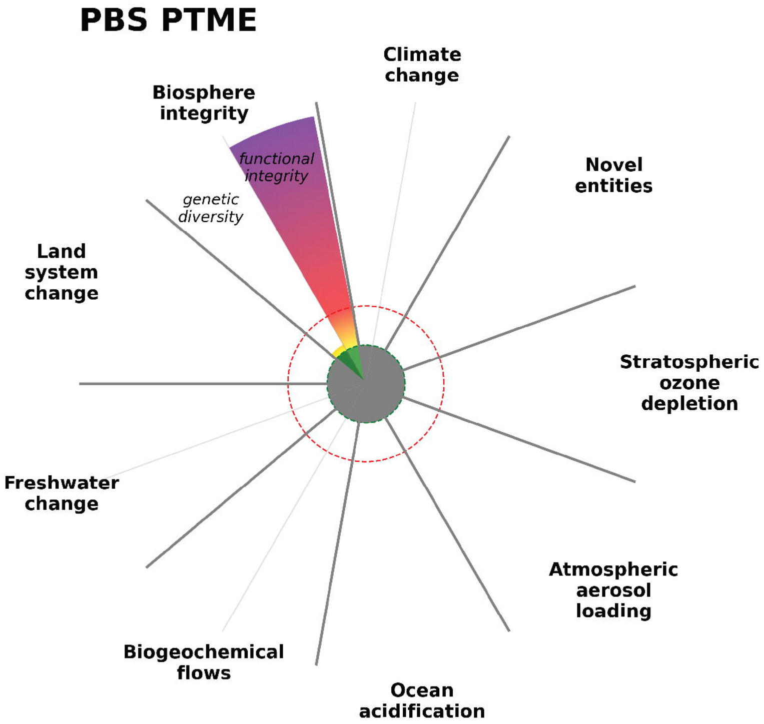
Table S2. Examples of persistent disruptors to the biosphere, from Hadean to contemporary times. Humans are included both as transient [grey boxed area] and potential persistent disruptors. Sources of information include [159] for gene transfer, [160] for RuBisCo, [161] for symbiogenesis, [162] for sexual reproduction and references in text.

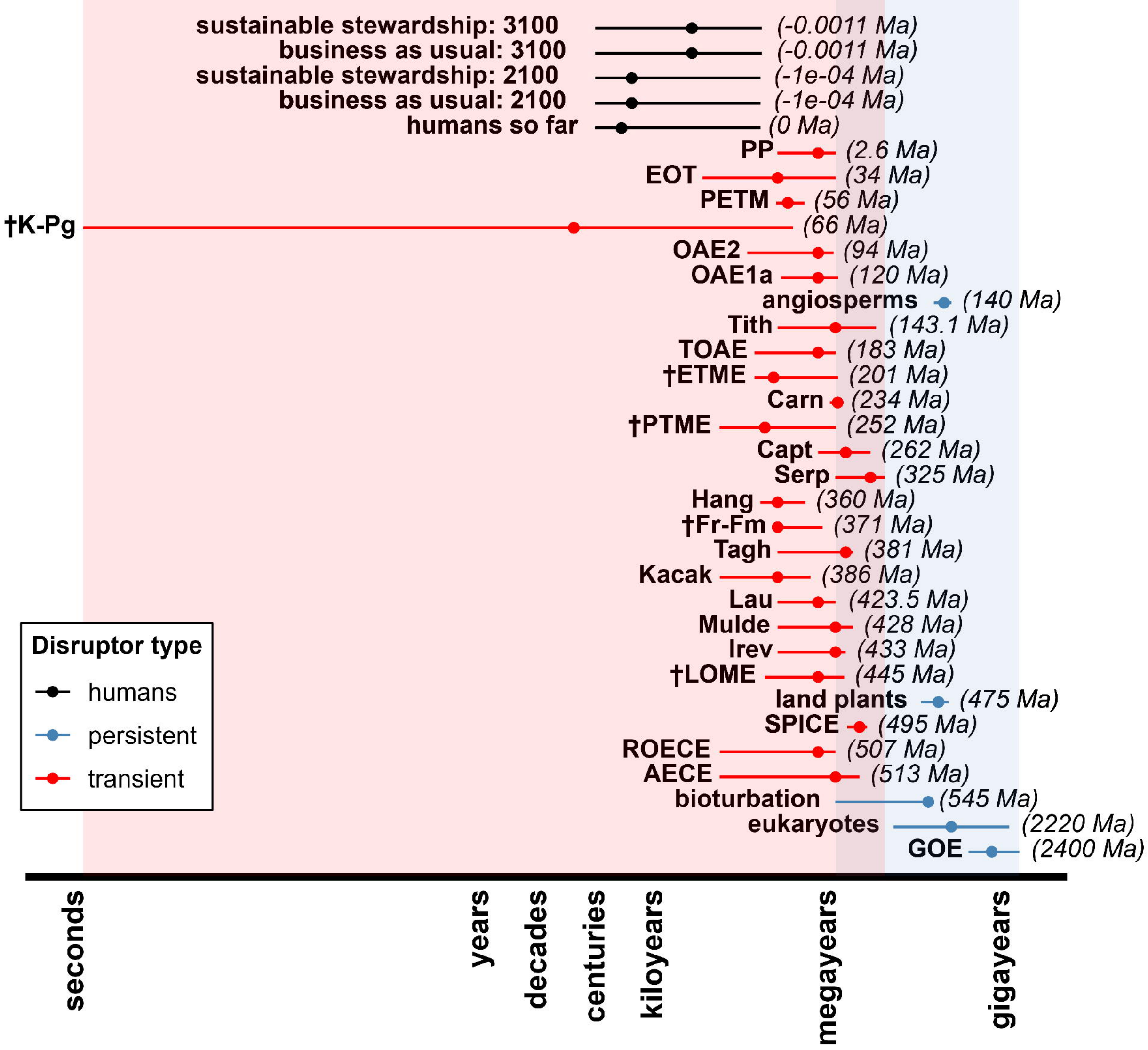
Table S3. The ages and duration of impact of transient and persistent disruptors in Earth history. These data are shown in figures 2 and 3 and are used to calculate the rates of change in figure 5.

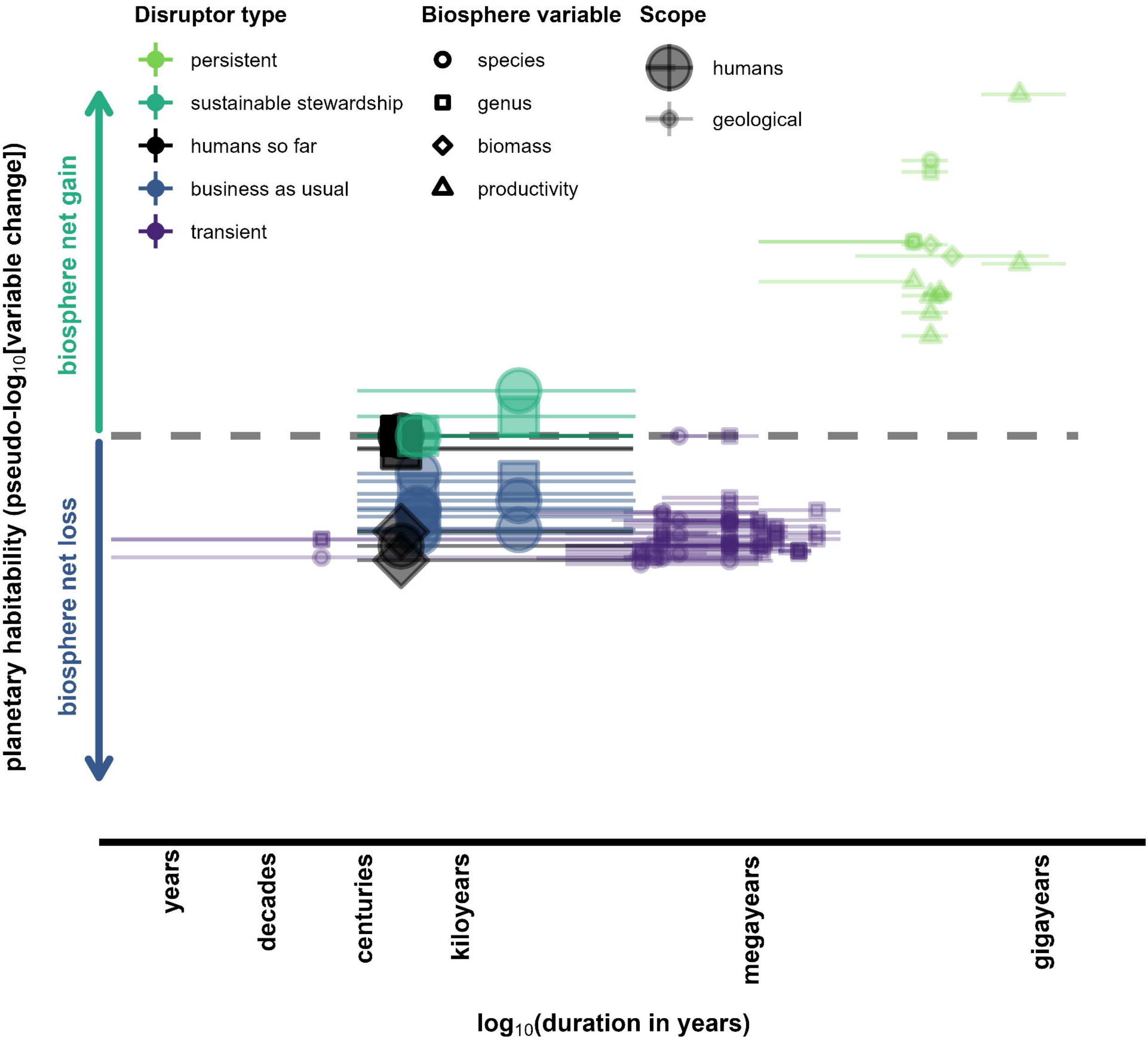
Table S4. Summary statistics of the event durations listed in Table S3.

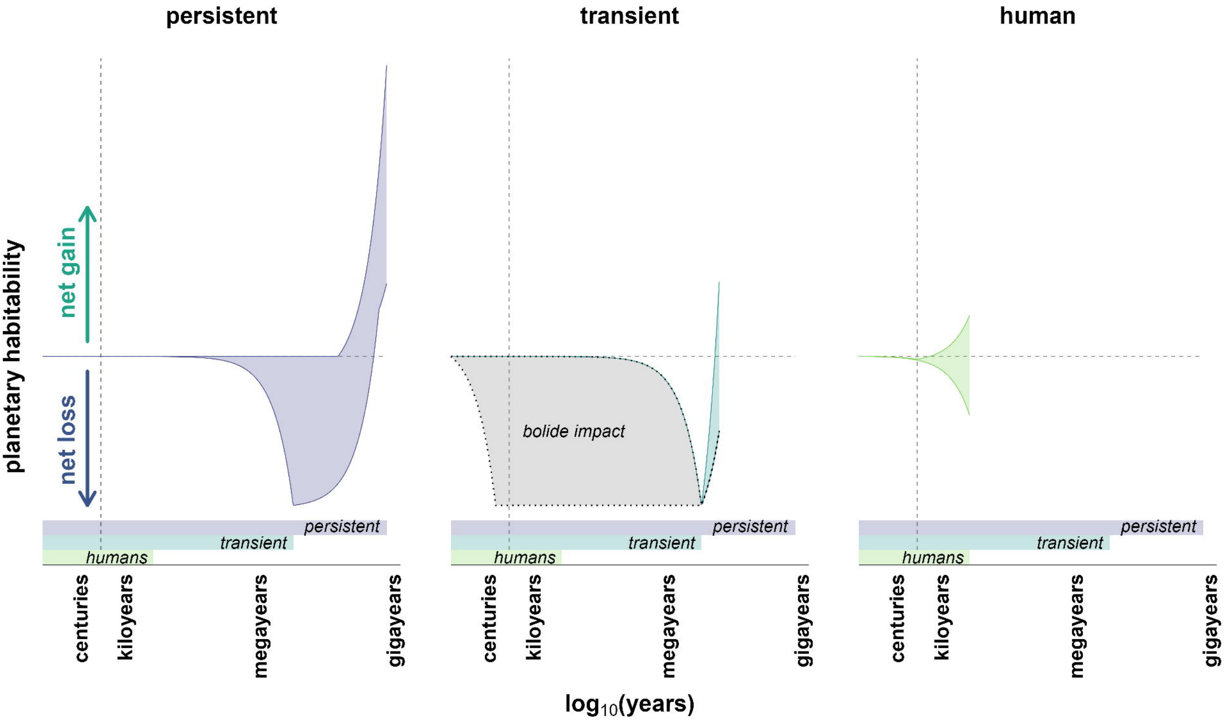
Table S5. The degree of change of four biosphere variables (species richness, genus richness, biomass, and productivity) through past transient and persistent disruption events and potential human futures. These data are shown in figure 3 and used to calculate the rates of change in figure 5.

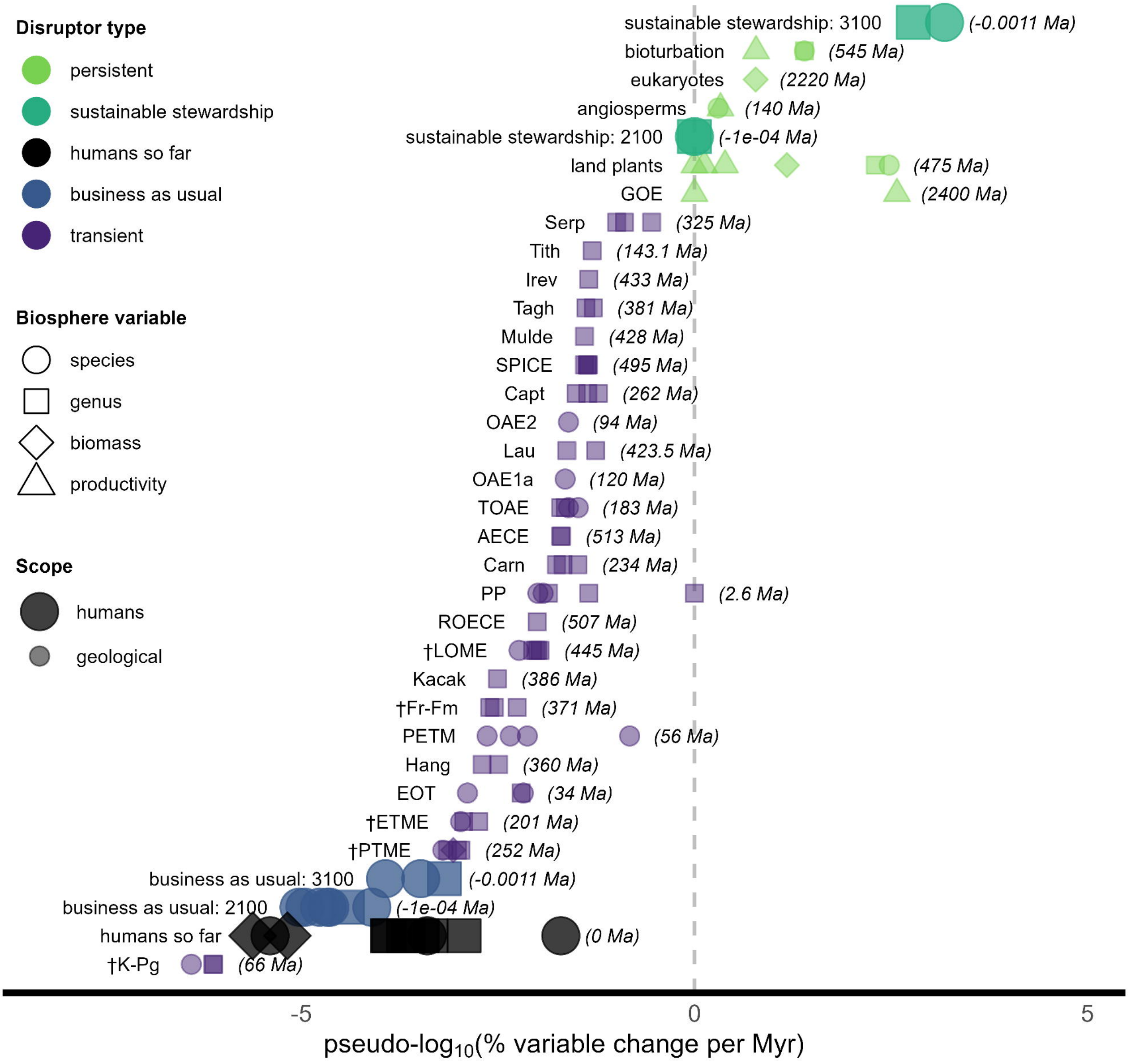

PBS 2025
Climate change
carbon dioxide
radiative forcing
Novel entities
novel entities
Stratospheric ozone depletion
ozone
Atmospheric aerosol loading
AOD
Ocean acidification
aragonite saturation state
Biogeochemical flows
phosphorus
nitrogen
Freshwater change
green water
blue water
Land system change
forest cover
Biosphere integrity
genetic diversity
functional integrity


PBS PTME
Climate change
Novel entities
Stratospheric ozone depletion
Atmospheric aerosol loading
Ocean acidification
Biogeochemical flows
Freshwater change
Land system change
Biosphere integrity
genetic diversity
functional integrity


sustainable stewardship: 3100 (-0.0011 Ma)
business as usual: 3100 (-0.0011 Ma)
sustainable stewardship: 2100 (-1e-04 Ma)
business as usual: 2100 (-1e-04 Ma)
humans so far (0 Ma)
PP (2.6 Ma)
EOT (34 Ma)
PETM (56 Ma)
†K-Pg (66 Ma)
OAE2 (94 Ma)
OAE1a (120 Ma)
angiosperms (140 Ma)
Tith (143.1 Ma)
TOAE (183 Ma)
†ETME (201 Ma)
Carn (234 Ma)
†PTME (252 Ma)
Capt (262 Ma)
Serp (325 Ma)
Hang (360 Ma)
†Fr-Fm (371 Ma)
Tagh (381 Ma)
Kacak (386 Ma)
Lau (423.5 Ma)
Mulde (428 Ma)
Irev (433 Ma)
†LOME (445 Ma)
land plants (475 Ma)
SPICE (495 Ma)
ROECE (507 Ma)
AECE (513 Ma)
bioturbation (545 Ma)
eukaryotes (2220 Ma)
GOE (2400 Ma)
Disruptor type
humans
persistent
transient
seconds
years
decades
centuries
kiloyears
megayears
gigayears


Disruptor type
persistent
sustainable stewardship
humans so far
business as usual
transient
Biosphere variable
species
genus
biomass
productivity
Scope
humans
geological
biosphere net gain
biosphere net loss
planetary habitability (pseudo-log$_{10}$[variable change])
years
decades
centuries
kiloyears
megayears
gigayears
log$_{10}$(duration in years)


persistent
transient
human
planetary habitability
net gain
net loss
bolide impact
persistent
transient
humans
centuries
kiloyears
megayears
gigayears
log$_{10}$(years)


Disruptor type
persistent
sustainable stewardship
humans so far
business as usual
transient
Biosphere variable
species
genus
biomass
productivity
Scope
humans
geological
sustainable stewardship: 3100
(-0.0011 Ma)
bioturbation
(545 Ma)
eukaryotes
(2220 Ma)
angiosperms
(140 Ma)
sustainable stewardship: 2100
(-1e-04 Ma)
land plants
(475 Ma)
GOE
(2400 Ma)
Serp
(325 Ma)
Tith
(143.1 Ma)
Irev
(433 Ma)
Tagh
(381 Ma)
Mulde
(428 Ma)
SPICE
(495 Ma)
Capt
(262 Ma)
OAE2
(94 Ma)
Lau
(423.5 Ma)
OAE1a
(120 Ma)
TOAE
(183 Ma)
AECE
(513 Ma)
Carn
(234 Ma)
PP
(2.6 Ma)
ROECE
(507 Ma)
†LOME
(445 Ma)
Kacak
(386 Ma)
†Fr-Fm
(371 Ma)
PETM
(56 Ma)
Hang
(360 Ma)
EOT
(34 Ma)
†ETME
(201 Ma)
†PTME
(252 Ma)
business as usual: 3100
(-0.0011 Ma)
business as usual: 2100
(-1e-04 Ma)
humans so far
(0 Ma)
†K-Pg
(66 Ma)
-5
0
5
pseudo-log$_{10}$(% variable change per Myr)