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Earth system interventions as technologies of the Anthropocene

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ABSTRACT

Earth system interventions (ESIs)—intentional large-scale interventions in Earth systems—are not entirely new. However, in response to threats to sustainability, particularly from climate change and biodiversity loss, some scientists and others are researching, developing, and using new, largely technological ESIs. These include carbon dioxide removal, solar geoengineering, in situ genetically modified organisms, gene drive organisms, de-extinction, and high-tech ecosystem restoration. Some emerging ESIs appear to be effective and feasible, both technically and economically, and may be necessary to achieve important sustainability and human welfare objectives. They also pose serious environmental risks. This paper identifies more than a dozen social, political, and ethical challenges that are common across many of the emerging technological ESIs. Governance could mitigate and manage these issues, and it would be made more effective and robust by understanding and treating new ESIs as such and as a potentially transformative set of innovations in human-Earth system relations.

1. Introduction

Humanity is qualitatively changing its relationship with the natural world. Our unintentional, harmful impacts on the environment are well known and, in the 20th century, clearly crossed to the global scale. Some researchers say that we may have surpassed some of the "planetary boundaries [that define] a safe operating space for humanity," among which are climate change, biosphere integrity, and altered biogeochemical cycles (Steffen et al., 2015 p. 736). Relatedly, scientists are debating whether the Earth has entered a new geological epoch, the Anthropocene, characterized by transformative human influence on major Earth systems (Zalasiewicz et al., 2017; Folke et al., 2021). The recognition that humanity possesses such a capacity has led to descriptive and predictive claims regarding our effects on Earth systems as well as a widespread normative belief that we should use this capacity responsibly.

Although most of these discussions concern humanity's inadvertent impacts, talk of intentional ones for sustainability objectives surfaces occasionally, as seen in writing regarding conservation interventions, technological transitions for sustainability, and planetary opportunities (Clark, 1987; Holling, 1996; Geels, 2002; Westley et al., 2011; DeFries et al., 2012; Karp et al., 2015). Here, *Earth system interventions* (ESIs) are intentional large-scale interventions in Earth systems. Furthermore, some scientists are researching, developing and, to a degree, using diverse new ESIs. Some of them appear to have the capacity to be effective and feasible, both technically and economically, and may be necessary to achieve widely endorsed goals of ensuring sustainability and improving well-being. Leslie Paul Thiele says of these interventions, "While they are anthropogenic (caused by humans), they are not anthropocentric (holding human needs and interests supreme)" (Thiele, 2020 p. 10). If emerging ESIs are adopted widely, humanity would

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clearly and collectively manage some Earth systems—even globally—constituting a genuine paradigm shift in how we relate to the planet and, by extension, to each other.

ESIs, especially the emerging ones, pose several social, political, and ethical challenges. Governance (here meaning the goal-oriented, sustained, focused, and explicit use of authority to influence behavior) could, and arguably should, reduce and manage these. For example, the environmentalism that motivates and undergirds much governance for sustainability rests, to a great degree, on beliefs in the balance of nature, limits to growth, and anti-anthropocentrism (Dunlap et al., 2000; Rauwald and Moore, 2002). This implies than many environmentally oriented persons believe that less intervention in the natural world is necessary for sustainability and inherently normatively desirable. But some new ESIs would be intentional interventions for sustainability purposes. Because the objectives are serious and are not being achieved through traditional means, and because the underlying techniques are being rapidly developed, ESIs and their challenges should be recognized, understood, and addressed as such to help make governance more effective and robust.

This paper offers a prospectus for the scholarship of ESIs and their governance. It argues that ESIs constitute an analytically useful, sufficiently coherent conceptual category; that emerging ones pose serious social, political, and economic challenges; and that the requisite governance would be improved by understanding and treating ESIs as a potentially transformative set of innovations in human-environment interaction. The next section elaborates on ESIs' definition, while the following two offer possible past and emerging ESIs. The paper then describes challenges that are common across ESIs, particularly the new ones. Having established the definition, cases, and challenges, Section 6 briefly reviews the existing scholarship of ESIs' governance. A synthetic discussion follows, tentatively exploring two lingering key questions. The conclusion summarizes and speculatively considers ESIs' role in humanity's long-term, hopefully sustainable future.

2. Intention and scale

ESIs' definition has two criteria: intentionality and large scale. Because each of these characteristics is continuous, the lines of distinction that I draw are not perfectly sharp and the cases thus debatable. The purpose here is to suggest, not to delineate and enforce sharp boundaries.

First, ESIs' environmental impacts must be intentional. This distinguishes ESIs from most past scholarly conceptualizations of large-scale interactions between humans and Earth systems (e.g. Liu et al., 2007). Humans' earliest significant effects on the natural world appear to have been mass extinctions of megafauna, particularly in North and South America, Australia, and the Pacific Islands. Other species were genetically shaped by the selective pressures of hunting. But these consequences were unintentional, and these human-nature interactions are therefore not ESIs.

Second, ESI's environmental impacts must spatially be large scale. A boundary of this could be that of a large ecosystem or a region, that is, at least thousands of square kilometers (km^2). For example, a settler might intentionally clear some trees to construct a house and grow crops, but this would be too small of a scale to be an ESI.

ESIs' criteria of scale and intention are somewhat interrelated. At one extreme, the intended and action actual could be large-scale if not global. Solar geoengineering, described below, is the epitome of this subcategory. But what of many small-scale actions that cumulatively have large-scale effects? This is the structure of many environmental problems. I suggest that such activities are ESIs only if some central decision-maker(s) intends the large-scale collective impact and advances it through innovation and/or policy. To extend the above example, many settlers might collectively clear an entire forest, but their intended environmental effects remain modest. However, if lawmakers incentivized them to do so with the objective of large-scale deforestation, then it would be an ESI.

One could argue that major efforts to reduce anthropogenic environmental impacts also constitute an ESI (Grinspoon, 2016). Instances here include efforts regarding acid rain precursors, ozone-depleting substances, and greenhouse gases. After all, such abatement is intentionally large scale, as evidenced by international treaties and other forms of cooperation. However, these efforts seek to end ongoing unintentional interventions in Earth systems. Whether doing so is itself an intervention resembles the distinction between commission and omission. My sense is that intentionally reducing large-scale impacts is not an ESI; others may disagree.

3. Possible past Earth system interventions

3.1. Agriculture

Humans have altered their environments for millennia, including intentionally and collectively at large scales. The Neolithic Revolution was a fundamental shift in how humans interact with Earth systems: from relatively passively gathering and hunting to more actively reshaping—if not creating—novel ecosystems to produce food, energy, and materials. Although agriculture has been the source of some of humanity's greatest environmental impacts, particularly through land-use changes, it appears to mostly not be an ESI because the intended effects remain small-scale. There are exceptions. Many contemporary farms (particularly dairy and beef ranches) are larger than 10,000 km^2, with the biggest at almost 100,000 km^2. And governments have implemented policies to increase agriculture's scale. For example, the United States' Homestead Acts (especially that of 1862) distributed about one million km^2 with the requirement that the land be improved (United States Bureau of the Census, 1975); most of this was subsequently farmed or ranched.

3.2. Landscape burning

Many Native American groups, especially in western North America, used fire to extensively modify landscapes (Vale, 2013). This increased the number and accessibility of game animals, encouraged the growth of gathered food and other useful plants, and allowed for easier travel. Although direct evidence of these fires' larger sizes remains weak, natural fires in these areas can reach thousands of km^2. Intentional fires may have done so as well, although Native Americans' intended scale may not have been so great. Therefore, this activity's status as an ESI is unclear.

3.3. Land and water

We have converted land into water, as well as the reverse, and distributed water over large areas of land. Humans have been damming rivers and streams since the 3rd or perhaps 4th millennium BCE. Since then, major reservoirs have grown to 8,500 km^2 (Lake Volta, Ghana). In terms of making new (usable) land, the scale of wetland drainage—primarily for agriculture—greatly increased in the late 19th and early 20th centuries. For instance, an 1859 state law facilitated the drainage of the 4000 km^2 Great Black Swamp, Ohio, US (Mitsch, 2017). Most famously, almost 20,000 km^2 of the Netherlands was originally below sea level. Most of this was drained over a few centuries in portions well less than 50 km^2. Spurred by an 1877 engineering plan, a political movement arose there to reclaim most of the Zuiderzee (South Sea). The Dutch government undertook this after the second World War, but this was not completed, yielding 1650 km^2 of new land and 1800 km^2 of desalinated lakes (Hoeksema, 2007). (Ironically, some of this new land now offers the Netherlands' most popular "wilderness" areas; Lorimer and Driessen, 2014). Large-scale irrigation became a serious possibility soon after the turn of the 20th century. A 1919 semi-official report spoke of "Irrigation of Twelve Million Acres in the Valley of California" (Marshall, 1920), a figure (about 49,000 km^2) that was approached (but far from reached) in midcentury. Several existing irrigation projects now are now upwards of 20,000 km^2 (e.g. India Today, 2019). These focused, state-driven projects—large reservoirs, land reclamation, and irrigation projects—are ESIs.

3.4. Intentional extinction

Humans have intentionally extinguished species or locally eradicated populations (meaning the interbreeding members of a species that typically live in a geographic place) thereof. In the 19th century, the American buffalo was hunted to near-extinction, to some degree intentionally, to allow more room for cattle and trains. The primary screwworm, an agricultural pest, was largely eradicated in the Americas through the in situ (that is, in the wild) introduction of large numbers of sterile individuals in the mid-20th century (Vargas-Terán et al., 2021). If viruses are considered living, then those such as smallpox have been intentionally extinguished, or nearly so.

3.5. Nitrogen cycle management

In the late nineteenth century, a global food shortage caused by a limit to usable nitrogen seemed imminent. Prominent scientists of the time recognized this challenge to humanity and called for an engineered response. For example, in his 1898 inaugural address as incoming president of the British Association for the Advancement of Science, William Crookes said, "The fixation of nitrogen is vital to the progress of civilised humanity. It is the chemist who must come to the rescue of the threatened communities. It is through the laboratory that starvation may ultimately be turned into plenty" (Crookes, 1899 pp. 46, 3). Spurred by this dark prospect, Wilhelm Ostwald, Henry Louis Le Chatelier, Carl Bosch, and Fritz Haber developed within twenty years technological innovations to convert—or "fix"—atmospheric into usable nitrogen. Now in widespread use, this enables food for billions of people. Humanity is now responsible for more than two-thirds of nitrogen fixation, and consequently collectively manages, in a way, the global nitrogen cycle (Socolow, 1999; Smil, 2004; Vitousek et al., 2013). Whether this constitutes an ESI is debatable. The scientists did intend a large-scale intervention into this Earth system and created the means to achieve it. On the other hand, it is unclear whether they envisioned the magnitude of contemporary anthropogenic nitrogen fixation.

3.6. Ecosystem restoration

As a final, most recent example, increasing awareness of ecosystems' use and non-use values, vulnerability, and degradation catalyzed the development of means to restore them. After initial endeavors throughout the 20th century, the practice of ecosystem restoration took shape in the 1980s (Jordan and Lubick, 2011). These interventions were always intentional and for conservation purposes, and their spatial scales have grown. Now, for instance, the US state Louisiana is undertaking an effort to rebuild 70 km^2 of degraded land near the mouth of the Mississippi River. The Bonn Challenge, led by Germany and the International Union for the Conservation of Nature, is working to restore 3.5 million km^2 of forests worldwide by 2030 (Dave et al., 2018). Restoration can be marine as well: several coral reefs have been repaired, such as through the placement of thousands of specialized concrete balls (Omori, 2019). Of these various projects, only the internationally coordinated efforts, such as the Bonn Challenge, currently satisfies ESIs' scale criterion.

When did ESIs arise? Historical agriculture, irrigation, and land burning lack intentional large-scale environmental effects. American bison eradication was incomplete and not aimed at extinction regardless. The 1859 Ohio law, and most of its contemporaries and followers, only authorized counties to establish local drainage districts, although these could suffice as an ESI. Serious consideration, research, and development of other ESIs—the Zuiderzee drainage and reclamation, nitrogen fixation, and major irrigation projects—began around the turn of the 20th century, while their large-scale implementation had to wait until the middle of the century.

4. Emerging Earth system interventions

Some ESIs that are presently being researched, developed, and—to some degree—used differ in important ways from the past ones. First, the intentionality of their large- and even global-scale effects is clearer. Second, most of these emerging ESIs use technologies of great leverage, that is, the ratio of impact to inputs of time, space, energy, and capital. Third, the scientists who are developing them are aware of, if not aiming to reduce, humanity's environmental impacts. Elizabeth Kolbert writes that the new developments are, compared with those of the past, "less in a spirit of techno-optimism than what might be called techno-fatalism" (Kolbert, 2021 p. 200). Specifically, the new ESIs largely aim to address the two greatest global environmental threats: anthropogenic climate change and declining biodiversity.

As with the two definitional criteria, the distinction between possible past ESIs and emerging technological ones are is sharp. The developers of artificial nitrogen fixation were cognizant of the likely effects to that element's global cycling. Landscape burning was a high-leverage technology. Twentieth-century ecosystem restoration was driven by ecological sensitivities. However, the emerging ESIs have most or all these features.

Some new ESIs are introduced below. This includes their physical and environmental risks, which vary among them and are relevant to governance.

4.1. Carbon dioxide removal

Reductions of greenhouse gas emissions will almost certainly be unable to prevent global warming from exceeding the internationally agreed-upon goal of 1.5 to 2°C (United Nations Environment Programme, 2020). Instead, doing so will require the removal of carbon dioxide—the most important greenhouse gas—from the atmosphere at very large scales and its safe, long-term sequestration (IPCC, 2018). Despite disclaimers in the 2013-2014 Fifth Assessment Report of the Intergovernmental Panel on Climate Change, the reliance on carbon dioxide removal (CDR) in forecasts that would likely keep warming within 2°C was initially not widely acknowledged (Anderson and Peters, 2016). Only recently has CDR been rapidly mainstreaming within the climate discourse, driven by the Paris Agreement's implicit endorsement of CDR (Articles 4.1, 5.1) and states' increasingly common "net zero" emissions targets. If CDR is undertaken at the necessary and assumed scales, humans would become conscious managers of the global carbon cycle.

CDR approaches have diverse means, capacities, risks, costs, uncertainties, and readiness levels (National Academies of Sciences, Engineering, and Medicine, 2019). Most generally, they can be divided into nature-based and technological methods. In the former, forests could be grown and ecosystems managed in ways that biologically sequester carbon. For purposes here, afforestation—the planting of forests where they did not previous exist—is particularly relevant as it, unlike other nature-based approaches, would intentionally create locally novel ecosystems. Globally, this could be 7 million km^2 (Zomer et al., 2008). Regionally, several African countries are creating a "Great Green Wall" of trees across the Sahel totaling about 120,000 km^2, primarily to reduce desertification. Among technological CDR methods are direct air capture, in which carbon dioxide is captured from ambient air, and stored (Gambhir and Tavoni, 2019) and enhanced weathering, in which minerals are processed to accelerate natural chemical carbon cycling (Beerling et al., 2020). Bioenergy with carbon capture and sequestration (BECCS), in which plants are grown and burnt to produce energy, with the resulting carbon dioxide captured and stored, combines nature-based and technological approaches (Hanssen et al., 2020).

The environmental risks vary among the techniques. BECCS and re- and afforestation require vast amounts of land, potentially reducing biodiversity and increasing food prices. BECCS and direct air capture need storage, which could leak. Enhanced weathering involves large-scale excavation, transportation, and processing, and could affect ocean chemistry.

4.2. Solar geoengineering

If aggressive greenhouse gas emissions reductions, CDR, and adaptation to a changed climate cannot rapidly, affordably, and safely scale up, then humans could reduce climate change by blocking or reflecting a small portion of incoming sunlight. The leading proposed technique of such solar geoengineering would replicate volcanoes' natural cooling effect by injecting aerosols into the stratosphere. This appears to be effective, inexpensive in its direct deployment costs (Smith 2020), technically feasible, and climatically reversible (IPCC, 2018 p. 350; National Academies of Sciences, Engineering, and Medicine, 2021). Another potential method would be to brighten low-lying marine clouds by spraying saltwater into the lower atmosphere (Stjern et al., 2018). After the water droplets evaporate, the remaining salt particles would act as cloud condensation nuclei. A third method would be to inject ice nuclei, such as bismuth triiodide, into the atmosphere where feathery cirrus clouds, which generally hold in heat, are likely to form (Gasparini et al., 2020). This would disperse these clouds. This cirrus cloud thinning is not strictly solar geoengineering but is sufficiently similar in key characteristics to be grouped therewith.

Solar geoengineering may be able to reduce climate change, but environmental risks include changed precipitation patterns (Irvine and Keith, 2020) and possible impacts on stratospheric ozone (Xia et al., 2017); others might remain unknown. Solar geoengineering is the only set of proposals discussed here that is widely recognized as an ESI per se (Schneider, 2001).

4.3. Genetic modification of in situ populations

The other emerging ESIs largely focus on conserving, restoring, and enhancing biodiversity. They could improve ecosystem integrity, function, and resilience; satisfy legal duties; fulfil environmental ethical obligations; and increase public support and optimism for conservation. These biological ESIs would, in most cases, be large scale but not global (although gene drive organisms could be). The various biotechnological methods overlap and can be considered a spectrum, perhaps under the label of "synthetic biology" (Reynolds, 2021).

Although the rise of transgenic biotechnologies since the 1970s raised the possibility of intentionally genetically modifying in situ populations, it was not until the development of more precise, faster, and less costly CRISPR-based methods in the 2010s that doing so became feasible (Corlett, 2017). Members of species could be genetically modified and released into their original habitats (Redford et al., 2019). This would generally require that the modification confer a reproductive advantage, allowing the gene and trait to propagate and perhaps dominate the population. In contrast, a reproductively disadvantageous modification would be outcompeted and fade from the population.

In situ genetically modified organisms (GMOs) could have diverse applications. One approach would be to confer disease resistance to a threatened species. For example, the American chestnut tree could be made insusceptible to the fungal blight that has nearly extinguished it (National Academies of Sciences, Engineering, and Medicine, 2019). The second set of applications is "assisted evolution," which would increase threatened species' resilience, often to climate change. Corals and/or their symbiotic microorganisms in Australia's Great Barrier Reef could be genetically modified to withstand warmer and more acidic marine water, both of which are due to elevated atmospheric greenhouse gas concentrations (Fidelman et al., 2019). This need not necessarily be done by genetic modification; selective breeding and release might suffice (van Oppen et al., 2017). The third set of applications would be for anthropocentric ends and include the release of disease vector or agricultural pest insects that have been genetically modified to die out, to not transmit the disease, or to not consume crops (Evans et al., 2019; Shelton et al., 2020). In this approach, large numbers of the GMO would need to be introduced, perhaps repeatedly so, because the modification would be reproductively disadvantageous, or at least not advantageous. As a consequence, the intervention's effect would be of limited temporal and spatial scale.

The most significant environmental concerns are that the genetic modification could affect the species in unexpected ways or spread beyond the target population or species, for instance via horizontal gene flow or hybridization (Convention on Biological Diversity, Secretariat, 2015 p. 82). The novel organisms could adversely affect ecosystems as well, perhaps by undesirably outcompeting the unmodified ones. Premature accidental release is also possible.

4.4. Gene drive organisms

In the second biotechnological ESI, humans could genetically modify in situ populations through gene drives, "systems of biased inheritance in which the ability of a genetic element to pass from a parent to its offspring… is enhanced" (National Academies of Sciences, Engineering, and Medicine, 2016 p. 15; see also Redford et al., 2019). Crudely described, a gene drive copies itself and an accompanying desired genetic sequence onto the equivalent location on an organism's other set of genes, causing both the drive and desired sequence to be transmitted to (nearly) all of an individual's offspring. Through this mechanism, humans could genetically modify an entire population, including for reproductively disadvantageous traits, by introducing only a small number of gene drive organisms (GDOs). Note that gene drives are effective only in sexually reproducing species that have a short life cycle. Most interest in engineered gene drives thus far has been in reducing the size of a local population or extinguishing it entirely, which could be achieved by causing most or all offspring to be male or members of one sex to be infertile.

The potential applications here include those of in situ GMOs: making endangered species resistant to disease, making them more resilient to climate change and other stresses, and to alter or eliminate populations of harmful species (Rode et al., 2019). GDOs could be especially effective in the latter approach, as repeated introductions of large numbers of organisms would not be necessary. In addition, GDOs could be used to suppress or eradicate populations of invasive alien species—one of the leading direct drivers of biodiversity loss—or make them less competitive with native ones. This is particularly appealing on islands, which are vulnerable to invasive species and could better contain a gene drive (Esvelt and Gemmell, 2017; Leitschuh et al., 2018; Godwin et al., 2019).

GDOs' environmental risks are similar to those of GMOs (Hayes et al., 2018), but gene drives' high-leverage justifiably causes greater concern. In fact, some researchers state that GDOs should be placed outdoors only when altering or eradicating all populations of the target species would be acceptable (Esvelt and Gemmell, 2017; Noble et al., 2018).

4.5. De-extinction

Various biotechnological methods could revive locally, functionally, or globally extinct species, or at least novel analogs thereof, and reintroduce them into an in situ habitat (Steeves et al., 2017; Novak, 2018). This would use a combination of selectively breeding similar species through back-breeding and hybridization, assisted reproduction, cloning, and genetic modification. Scientists are researching whether the quagga, heath hen, black-footed ferret, and others could be returned in this manner. De-extinction could revive a given species, improve and restore ecosystem functioning, and offer aesthetic rewards of wonder and awe (Greely, 2017).

The environmental risks of de-extinction are dependent on the methods at hand. To the extent that it utilizes genetic modification, those of GMOs would arise. In addition, the introduction of a de-extinguished species into an ecosystem would, in some ways, resemble that of an invasive alien one (Greely, 2017; Valdez et al., 2019). After all, most ecosystems have changed significantly since the species became extinct. What the reintroduced species would consume, what would consume it, and how it would compete will be somewhat uncertain. Furthermore, a revived species could pose unexpected disease risks, including to humans (Valdez et al., 2019).

4.6. High-tech ecosystem restoration

As described above, humans have been restoring ecosystems, as the concept is currently understood, for more than a century. While knowledge advanced, most of the methods remained rudimentary, such as identifying species or indicators thereof visually, cataloging and mapping with paper and—more recently—computers, and relocating species and specimens physically. In some cases, such as in the Florida Everglades, ecosystem restoration has become more extensive and intensive (Gunderson and Light, 2006). But the available technologies are currently leaping forward. Unoccupied aircraft—"drones"—can conduct spatial reconnaissance as well as rapidly and precisely distribute seeds (Ridge and Johnston, 2020), while machine learning and artificial intelligence are poised to increasingly analyze data, detect patterns, and develop plans. Taken together, these technological developments point toward a future in which humans manage and restore some ecosystems via advanced information technologies. A low-tech ESI is becoming a high-tech one.

5. Social, political, and ethical challenges

Some emerging ESIs have substantial capacity to facilitate sustainability and to improve human well-being, and their use in the near future seems increasingly likely. They also pose serious, diverse environmental risks and social, political, and ethical challenges, and will thus often be contested. As such, ESIs' governance will be important.

Existing legal instruments can manage many of the environmental risks, described above, for the various new ESIs. For example, most countries require prior environmental impact assessment of proposed projects and programs that create a risk of significant environmental harm. Because researchers, materials, knowledge, and impacts cross jurisdictional borders, governance will need to be—to some degree—international. Extant international environmental law can regulate many transboundary risks, and numerous scholars have reviewed applicable national and international law (Reynolds, 2018, 2020). For example, CDR appears to fall under the purview of the international climate change regime, and the biodiversity regime regulates the international movement of many GMOs. The parties to the Convention on Biological Diversity have taken up the governance of synthetic biology, a poorly defined term that would encompass most of the biotechnological ESIs discussed here.

However, existing governance mechanisms, procedures, and institutions sometimes fail to assuage concerned observers because apprehensions are not limited to environmental, human health, and other physical risks. Some of the social, political, and ethical matters that are common across many—but not necessarily all—emerging ESIs are introduced here. Some of these arise in other cases of governance, especially of international, technological, environmental phenomena. But in the case of ESIs, observers emphasize these, and some emerging technological ESIs could amplify these challenges. Together, these issues suggest that it may be beneficial to consider ESIs as a category or perhaps an object of governance, at least in some regards.

5.1. The goal of environmental governance

Perhaps the highest-order matter is why govern activities as they relate to the environment. ESIs require us to interrogate and explicate these objectives. Are they to restore pre-industrial conditions as much as possible, to help humanity sustainably thrive, to compensate for past wrongs, or something else? For example, the seventeen UN Sustainable Development Goals include

End poverty in all its forms everywhere…

Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all…

Take urgent action to combat climate change and its impacts… halt biodiversity loss. (United Nations General Assembly, 2015)

As long as a smaller footprint of human activities coincides with sustainability, then any ambiguity in environmental governance need not be resolved to use and govern ESIs. At the same time, the threats of climate change and sharp biodiversity reductions coupled with technological ESIs' prospect highlight underlying tensions.

Environmentalism and the scholarship of environmental governance are dominated by a sometimes-implicit normative preference for the natural. Moreover, since World War II and especially since the mid-1960s, environmentalism in industrialized countries has been generally skeptical of new, large-scale, centralized, and unseen technologies. To use the terms of Charles Mann, environmentalism and environmental governance scholarship have been dominated by "Prophets"—those who call for humanity to contract its activities and impacts in order to protect our fragile natural nest—while largely sidelining "Wizards"—those who see technology overcoming environmental challenges and consequently envision an "ecomodernist" future (Mann, 2019; see also Symons, 2019). This leaves them seemingly ill-suited for responding to ESIs' possible transformation of how humanity interacts with Earth systems.

But the extent to which this dominance in environmentalism and scholarship transfers to actual environmental governance is not clear. International environmental law, at least, has been increasingly shaped by developing countries, which generally prioritize human needs—especially economic development—over those of nature. Indeed, a leading textbook on the subject states that "almost all justifications for international environmental protection are predominantly and in some sense anthropocentric" (Birnie et al., 2009 p. 7).

5.2. Displacement of other responses

Some observers are concerned that the research, development, and use of new technological ESIs could undermine other efforts—such as greenhouse gas emissions reduction and habitat conservation—that address problems closer to their causes. This is explicitly evident in at least CDR (Markusson et al., 2018), solar geoengineering (Reynolds, 2015), and de-extinction (International Union for Conservation of Nature, Species Survival Commission, 2016; Bennett et al., 2017). The concern of obstructing and displacing other responses may be rooted, to some degree, in the above-described common preference for less intervention in nature. But beyond this, there are also issues of competition for limited resources among potential means to an objective (Valdez et al., 2019; Sandler, 2020), delaying action now due to the prospect of uncertain future technologies (Fuss et al., 2014), and how to integrate ESIs into a robust portfolio of responses (Jebari et al., 2021).

This concern of potentially-displaced, widely-preferred and/or dominant responses is understandable, but how governance could and should act is unclear. For one thing, if we assume that the sustainability goals are to prevent climate change impacts and biodiversity loss, then some displacement may be an acceptable "price" to pay for greater progress toward those goals via the ESIs. In other words, rejecting the ESIs could do more harm than good in terms of these goals. Furthermore, policymakers often support measures and technologies that reduce risk even when the measure or technology causes a compensating increase in the underlying risk-causing behavior. Think of, for example, seat belts and other safety equipment in cars, which lead to less-safe driving but overall fewer injuries and deaths. It is usually only when the underlying risk-causing behavior is seen as immoral that such measures and technologies are resisted. Here, think of sex education for adolescents and harm-prevention measures for users of illicit drugs. In these cases, some people's goal is the reduction of risk and harm while for others it is preventing immoral behavior. Are greenhouse gas emissions and habitat destruction immoral? Would they be (or seem) less so if their negative consequences were partially or fully ameliorated by ESIs?

5.3. Risk-risk trade-offs

Emerging ESIs are being developed to reduce severe environmental risks and threats to human health, while they also pose environmental risks of their own. There neither a justification to focus on only one of these sets of risks nor an obvious optimal path forward, only paths that are less bad. Although risk-risk trade-offs seem mundane (after all, we make them every day), environmental governance and risk regulation have largely not been crafted with them in mind (Graham and Wiener, 1995).

In the governance of risks, especially technological and environmental ones, that are low probability, high impact or remain uncertain, precaution is often invoked as a guiding principle. The two central global legal agreements in the domains where these ESIs would operate—the UN Framework Convention on Climate Change and the Convention on Biological Diversity—contain the precautionary principle (Article 3.3 and preamble paragraph 9, respectively). This operationalization of risk aversion is defensible, if not appropriate, in cases where the risks are public, widespread, or nonexcludable and any benefits of the risky activity are private, local, or excludable. However, it offers less guidance—and can even confuse thinking—when both the risks and the activity's benefits (including reducing other risks) are public, widespread, or nonexcludable (Sunstein, 2005). The emerging technological ESIs here pose such public risk-risk trade-offs. In part because of precaution's inability to guide decision-making in such a context, the decisions of the parties to the Convention on Biological Diversity on climate-related geoengineering (including large-scale CDR; decisions X/33, XI/20, and XIII/14) and synthetic biology (decisions XII/24, XIII/17, and 14/19) are somewhat muddled and contentious.

5.4. Deep uncertainty

Technological ESIs and the problems that they would address are characterized by uncertainties regarding risks and potential benefits. Humanity has never intentionally altered the genomes of in situ populations or changed the climate. It is more accurate to describe this condition as ignorance, in which we do not even know what some of the impacts may be (Faber et al., 1992). This could be characterized variously as a Collingridge dilemma ("attempting to control a technology is difficult…because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow"; Collingridge, 1982 p. 19), a wicked problem ("those that are complex, unpredictable, open ended, or intractable"; Head and Alford, 2015 p. 712), or post-normal science (where "facts are uncertain, values in dispute, stakes high, and decisions urgent"; Ravetz, 1999 p. 649).

The common response to this deep uncertainty is to develop policy well before problems manifest. Yet despite the innumerable articles, chapters, and books on "anticipatory governance," "foresight," and related approaches (Weber, 2006; Guston, 2014), this is difficult. As ignorance implies and as Collingridge said, we presently know neither what we (do not) want nor what might (not) happen.

5.5. Technological lock-in and "slippery slopes"

Another response to uncertainty is to accelerate research, which in principle should reduce the uncertainty. Some critics object, though, that doing so could unduly bias future decision-making in favor of using the ESI (Callies, 2019a). Such technological "slippery slopes" are typically suggested to come about through one of two general categories of mechanisms (Foxon, 2014). One is rational, in that actors need only pursue their own welfares given the available options and knowledge. Network effects and other increasing returns to adoption can lead to technological lock-in, while vested interests can grow and influence decision-making. The other category is ideational, in which the public and especially decision-makers increasingly think that the technology at hand is the preferred response to the problem. Similarly, another undesirable consequence of early steps could be a widening of purpose, in the cases of ESIs from conserving biodiversity and saving human lives to enhancing and optimizing nature to maximize human welfare.

A true slippery slope requires that desired early actions unduly increase the chance of unwanted future actions. After all, increasing the chance of a desirable subsequent action would not be problematic. More subtly, it not always clear whether duly increasing the chance of an unwanted future action is a problem, because this could be accompanied by a benefit, such as helping resolve whether the later possible action would be desired. For ESIs, research and development presumably increase the probability of their later use, as use requires research and development. However, the increase may not be undue, and their later use may not be unwanted. Thus, slippery slope claims are often oversimplifications of a dilemma.

Despite the fact that slippery slopes can be real—including the case of ESIs—but are subtle and complex (Volokh, 2003), claims are typically vague and often logically weak. Usually, they describe only very briefly how an ESI's research and development could unduly increase the chance of future use while trying to remain agnostic regarding the ESI's desirability (e.g. Lin, 2020). Furthermore, they don't consider the barriers associated with research and development that unduly decrease the chance of use, a situation that could be an "uphill struggle" (Bellamy and Healey, 2018). In contrast, others assert or assume that the ESI's potential future use is necessarily unwanted.[1] However, this is not a slippery slope argument, even though it appears to be, but one of comprehensive opposition.

Furthermore, as with potentially displaced preferred responses, it is unclear what governance could accomplish, and how. Ideational mechanisms are particularly difficult to regulate, as they concern the internal mental processes of numerous actors. In contrast, some possibilities that could reduce rational slippery slope mechanisms are diverse research programs, "red team / blue team" approaches that identify both benefits and shortcomings, and transparency mechanisms (Callies, 2019b).

5.6. Public good character

New technologies are typically developed by private actors who hope to profit from licensing the invention or selling the product. The resulting products and services can be sold to those who are willing and able to pay and be withheld from those who are not, enabling profit-driven development and marketing. In such cases, policymakers should be vigilant for the associated problems of firms unjustifiably hyping their innovations, patenting their inventions, and influencing public decision-making. Again, most ESIs are different, as their benefits (and negative impacts) will have large spatial and temporal spillovers. Whoever reduces climate change by solar geoengineering or CDR, restores an endangered species through in situ GMOs, eradicates a population of an invasive species by GDOs, or revives a species through de-extinction would capture only a small share of the benefits, which would be distributed across the region or globe. From an economic perspective, ESIs will generally be public goods—nonexcludable and nonrivalrous—which must be subsidized or provided by state actors. We should thus be less concerned with private firms' influence and more with whether policy sufficiently supports ESIs' responsible research, development, and—if appropriate—use. Furthermore, some of them would be global public goods (Barrett, 2007), suggesting that both domestic action and global cooperation may be required to ensure that ESIs move forward appropriately.

At the same time, there are important roles for for-profit entities in providing public goods. They can provide ESI-related goods and services at the behest of public bodies, perhaps through procurement. The firms can consequently be motivated to innovate and patent resulting inventions, allowing them to provide the good (or service) better, fast, and/or at a lower price than their competitors. There are also good reasons, both welfarist and deontological, to hesitate at for-profit firms playing large roles in intentionally modifying Earth systems at large scales. The governance of ESIs should recognize private actors' potential roles—including in beneficial innovation—as well as the pitfalls, and develop policy accordingly. In this, intellectual property will be central, and nontraditional regimes should be considered (Esvelt, 2017; Mitchell et al., 2018; Reynolds et al., 2018).

Another issue that derives from ESIs' public good character regards compensation for negative impacts. An actor who harms another can typically be held liable for that harm. Knowing this, he or she will exercise precaution at a degree that approaches optimal. However, liability for harm would cause potential providers of public goods, such as ESIs, to refrain from providing them. Nevertheless, harmed parties should be compensated for multiple reasons: to maintain public support for widely beneficial activities, to make victims whole, and to incentivize optimal levels of care and activity. Instead of liability, pooled compensation funds may be preferable (Horton and Keith, 2019).

5.7. Decision-making authority

By definition, ESIs have large-scale effects. Who—if anyone—has the legitimate authority to undertake them, especially the highly leveraged technological ESIs? This is clearly a matter of international relations in the case of those with potential global impacts (Reynolds, 2019). But decision-making is partially an international matter even with the merely large-scale ESIs, such as CDR (Lin, 2018; Brent et al., 2018), in situ GMOs (Reynolds, 2021), and de-extinction (Valdez et al., 2019), due to the deeply held values at stake, the transboundary problems that they seek to remediate, and the risk of even larger-scale impacts. Authorization mechanisms can be easy to propose but, because of international law's consensual basis, would often be difficult to implement. The participation of those countries that are most interested in using the given ESI, perhaps due to their vulnerability to climate change or biodiversity loss, would be most necessary but least likely. The issue of decision-making authority points to other challenges: how states and other actors may and would react to unwanted use of ESIs, whom must be consulted or even who should give their consent (Singh, 2019; George et al., 2019), and the role of private actors in decision-making (Babcock, 2019).

[1] This was evident in a recent controversy. A Harvard University team has been planning for years to launch a controlled balloon to release a ~2 kg of material into the stratosphere to observe chemical and physical responses to potential solar geoengineering (Dykema et al., 2014). After moving the intended site to Sweden, some local advocacy groups issued letters of protest, including after the scientists decided to merely test the equipment, launching but injecting no substances. The groups' arguments were largely that solar geoengineering should never be used and that research could only make use more probable. The test was indefinitely postponed on the prompting of the project's Advisory Committee.

5.8. Distributional concerns

Like all major public policies and new technologies, ESIs have heterogenous effects. Some people and groups would (perceive to) benefit more than others; some might even (perceive to) be harmed. Distributional concerns are particularly acute in the case of ESIs. This poses the classic political question of "who gets what, when, how" (Lasswell, 1936). As examples, someone must pay for endeavors such as CDR that produce a global benefit (Pozo et al., 2020), while some CDR techniques could pose local environmental risks. A key issue with solar geoengineering has been its expected heterogenous effects (Preston, 2016). And the introduction of genetically modified or revived organisms could have negative economic impacts through reduced tourism or competition with valuable other species (Barnhill-Dilling et al., 2019; Grunewald, 2019). In principle, wealth transfers from the "winners" to any "losers" can usually cause everyone to experience net benefits, but this is not always possible, much less actually done in practice.

5.9. North-South divisions

With respect to governance, a particular challenge with ESIs is that the expected or actual net effects might fall along common axes of international disagreement, especially between industrialized countries of the Global North and the developing ones of the Global South. This is because the techniques would presumably be primarily researched and developed in the former, while the most is at stake in terms of climate change impacts and biodiversity in the latter.

In this case, one might recall the most salient existing technology—agricultural transgenic GMOs in the 1990s and 2000s—that some industrialized countries promoted and some developing ones resisted (Pollack and Shaffer, 2009). However, the new ESIs seem different, as described in Section 4, in that their developers not only appear more aware of potential environmental impacts, but also seek to reduce them. Developing countries are the most vulnerable to climate change; all else being equal, additional means to reduce it should work to their relative favor (Harding et al., 2020). While their responses to the biotechnological ESIs for biodiversity purposes remain uncertain, the use of in situ GMOs and GDOs to reduce infectious diseases may be a decisive factor. Specifically, malaria, which accounts for half of a million fatalities annually, mostly in sub-Saharan Africa, and is the fifth leading cause of death there, could be eradicated through these ESIs. Indeed, Africa's support for them was evident at the most recent Conference of Parties to the Convention on Biological Diversity (Reynolds, 2020).

5.10. Malicious use

Critical observers sometimes claim that technological ESIs could be used maliciously. For example, agricultural pests or infectious insects could be equipped with a gene drive (National Academies of Sciences, Engineering, and Medicine and Medicine, 2018). Others suggest that solar geoengineering could be weaponized, militarized, or used for strategic relative gain (Adger et al., 2014, 2014 p. 777; Surprise, 2020). Whether ESIs actually could be effectively weaponized remains unclear, as they are generally only weakly targetable and difficult to withdraw quickly in response to the target's concessions.

5.11. Potential for nonstate governance

Governance is not just legal in character but includes also nonstate actors' intentional steering of behavior. Despite technological ESIs' high stakes, nonstate actors have substantial potential to govern them (Reynolds and Parson, 2020). One reason for this is that, in some cases, governments are reluctant to act. (This, in turn, may be due to how ESIs lie somewhat orthogonal to traditional environmental politics.) Another reason is that ESIs are technical, and only the scientists themselves possess certain requisite knowledge for governance. Finally, knowledge of the technologies' potentials, limitations, and risks can develop and change rapidly. Legal governance by state actors is slow to change, whereas nonstate governance can be more dynamic. Importantly, this is not to claim that nonstate governance is necessarily preferable to its state counterpart.

5.12. Public communication and understanding

Stakeholders and the wider public should be appropriately engaged on issues of ESIs, which could otherwise become more controversial, with debates polarized and divisive. Specifically, the public may initially react negatively to technological ESIs, as many have the criteria—for example, invisible, out of one's control, and dreadful—of phenomena where lay views differ significantly from those of experts (Sjöberg, 2004; Brossard et al., 2019; Kohl et al., 2019; Valdez et al., 2019).

Related to this is the optimal role of the public in decision-making. ESIs have a technocratic air about them, in which distant and possibly unaccountable experts make decisions with widespread, powerful effects. We are in also a time of reaction, on both the political right and left, to expertise and technocratic decision-making. This further points toward public engagement's importance and some degree of decision-makers' accountability to the public (Carr et al., 2013; Valdez et al., 2019; Jones et al., 2019).

5.13. Ethics

Finally, ESIs raise multiple serious ethical issues (Svoboda, 2017; Lenzi, 2018; Callies, 2019c; Sandler, 2020). Some relate to the social and political challenges identified above, others not. Genetically modified or especially de-extinguished animals may suffer physically or, in the latter case, even psychologically (Kasperbauer, 2017; Browning, 2018). Highly leveraged ESIs raise complex questions such as those concerning hubris (Callies, 2019a; Sandler, 2020), mastery over nature (Wapner, 2014), excessive optimism in technology (Valdez et al., 2019), and implications for human-nature relationships (Greely, 2017). For instance, Thiele says that the in situ uses of advanced biotechnologies “may become dominant forces for conservation in an age of global ecological crises, providing a crucial means of protecting and sustaining the natural world. Yet they stretch, if not tear apart, the very meaning of nature” (Thiele, 2020 p. 10). Of course, in a risk-risk trade-off, there are likewise strong ethical arguments to research, develop, and use ESIs (Gyngell and Savulescu, 2017; Morrow, 2020).

6. Existing governance scholarship

Although the emerging ESIs differ in important ways from past ones, there is a modest existing scholarship on environmental ESIs and their governance. As early as 2001, the chairs of four international global environmental change research programs agreed to the “Amsterdam Declaration” that established the Earth System Science Partnership (now reorganized and expanded as Future Earth):

An ethical framework for global stewardship and strategies for Earth System management are urgently needed the business-as-usual way of dealing with the Earth System is not an option. It has to be replaced—as soon as possible—by deliberate strategies of good management that sustain the Earth’s environment while meeting social and economic development objectives (Moore et al., 2001).

The only scholar to substantially explore ESIs as a category and their governance is Braden Allenby, who offers a conceptual framework. He proposed a concept of “Earth systems engineering and management” because humanity was already perturbing and intervening in Earth systems; recognizing this would help ensure that this is done responsibly (Allenby, 1998). Allenby asserts that we should expand our conception of engineering and management to “the scale of the technological and cultural systems that are, in fact, now beginning to dominate the dynamics of many natural systems” (Allenby, 2000 pp. 12–13). He proposes a handful of theory, design, and governance principles, such as minimal intervention in complex systems; democracy, transparency, accountability, and inclusive stakeholder dialogues; adaptive governance; and integration between technical experts and decision-makers (Allenby, 2005 pp. 185–187).

Other bodies of scholarship are salient to ESIs’ governance and can contribute indirectly, but their utilities remain limited for diverse reasons. First, scholarly analyses of some of the specific technological ESIs have varying degrees of robustness and coherency (Moe and Røttereng, 2018; Reynolds, 2019, 2020; Thiele, 2020). However, these discussions remain fragmented across the various activities, and the authors typically do not conceptualize the activities as ESIs per se (although solar geoengineering is an exception). Second is the Earth System Governance (ESG) project, which descends from the above Amsterdam Statement and has explored political responses to and governing institutions for sustainable development. ESG scholarship offers shared vocabulary, tools, and prescriptive guidance for understanding ESIs and their governance, and the project’s research plan has the Anthropocene and “transformations… of linked socio-technical-ecological systems” as contextual conditions (Burch et al., 2019). Yet ESG scholars have mostly not considered ESIs, and when they have, generally reject them. For example, its founding chair described Earth system management as “both infeasible and—in its connotation of hierarchical planning—undesirable” (Biermann, 2007 p. 326; see also Dryzek, 2016; Gupta and Möller, 2019; but see Galaz, 2014). Third, some scholars have developed a handful of synthetic theories of the law and regulation of emerging technologies (Moses, 2007; Mandel, 2009; Brownsword and Goodwin, 2012; Marchant et al., 2013). These emphasize anticipating possible effects, the dilemma of developing policy before risks and impacts manifest, high stakes risk-risk trade-offs, decision-making under uncertainty, maintaining connection between dynamic technologies and static public policy, and the challenge of diverse ethical foundations and legal contexts. One important distinction with ESIs, though, is that this literature generally assumes that commercial actors develop and market technologies, sometimes contrary to the wider public interest. However, as described, most ESIs’ spatially uncontrolled nature causes them to be public goods. Finally, although research in planetary boundaries and the Anthropocene aims to take a “bird’s eye view” of humanity’s complex relationship with the biosphere, ESIs may be a blind spot here. For example, while a recent comprehensive review of this domain did touch on emerging technologies’ role in fostering or undermining sustainability, it gave substantive attention to only artificial intelligence-informed environmental management (with a passing mention of carbon dioxide removal) (Folke et al., 2021 pp. 848–849).

7. Discussion

A few key questions remain, each of which warrants further exploration. The first is whether ESIs indeed constitute an analytically useful if not coherent conceptual category. On the one hand, the emerging and proposed ESIs seem novel and pose multiple social, political, and ethical challenges, many of which are common among them. On the other, the issues of past ESIs are no longer particularly salient. Neither scholars nor activists raise alarms regarding—for example—technological lock-in, decision-making authority, distributional concerns, and ethics of nitrogen cycle management. This suggests that the challenges are primarily (if not entirely) prospective and are often resolved, such as through governance, adaptive responses by ESIs’ developers, and changes in public attitudes and preferences; that the new ESIs are distinct from extant ones; and/or that the current socio-political world differs from the past in important ways.

Second, if some form of governance that recognizes ESIs as such would be beneficial, where and in what form might it arise? Although many scholars of environmental governance are quick to call for further international law, this seems unlikely and unwanted. Because technologies can develop rapidly, governance must be nimble, which is more often found in institutions that represent smaller jurisdictions and that are less legal in character. Furthermore, state actors have relatively little incentives to move toward oversight of controversial techniques that could both reduce and increase environmental risks. Instead, governance of emerging ESIs will probably develop among multiple paths: state and nonstate; global, international, national, and subnational; applicable to an entire ESI and to a specific issue thereof; and promoting and restricting activities. That is, it may be polycentric and/or fragmented, depending on the extent to which mechanisms are complementary or conflictual.

An implication of this plural governance is path-dependency: how ESIs are governed early will shape future governance. For instance, early coupling of CDR and solar geoengineering as "geoengineering" (Institute of Medicine et al., 1992) has caused these two arguably distinct ESIs to be linked, hindering their effective governance (Jinnah et al., 2021). Likewise, early interest in ocean fertilization as a possible—but risky and controversial—CDR technique (Strong et al., 2009) catalyzed international governance of not only it but all CDR and solar geoengineering that would take place in the marine environment (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, 2019). A comparable issue regarding the biotechnological ESIs is being debated in various forums: Should these be grouped as synthetic biology or something similar, or should they and related applications be differentiated?

Finally is the question of whether an environmental framing is the optimal approach ESIs' governance. At the very least, environmental governance could become paralyzed because emerging technological ESIs cut right to the heart of environmentalism's normative frameworks, despite these often being unstated, implicit, and ambiguous. More acutely, such a framing could elevate some systems and values—environmental and arguably Western ones—and relegate others—developmental, cultural, and even religious ones—to relatively lower profiles (Allenby and Sarewitz, 2011). If so, then ESIs may indeed call for a more distinctive approach to their governance.

8. Conclusion and outlook

Earth system interventions (ESIs) are intentional large-scale interventions in Earth systems. Some already exist: land reclamation, reservoirs, irrigation, intentional extinction, nitrogen cycle management, and ecosystem restoration. Emerging technological ESIs are distinct in a few key ways, and some appear both feasible and necessary to achieve important sustainability and human welfare objectives. Among these mostly technological methods are carbon dioxide removal, solar geoengineering, genetic modification of in situ populations, gene drive organisms, de-extinction, and high-tech ecosystem restoration. Dedicated, informed governance of emerging technological ESIs that takes their interventionist nature into account appears warranted due to their combination of potential effectiveness, increasing chance of use, feasibility, physical risks, social and other challenges, and political contestation. I assert that prospects for effective, legitimate governance would be strengthened by recognizing ESIs as such and as a possible transformative innovation in human-nature relations.

Astrobiology—"the study of the origins, evolution, distribution, and future of life in the universe" (NASA Astrobiology Institute, 2018)—may seem a strange field to which to turn for how humans might interact with Earth systems to achieve sustainability. Yet just as the field extrapolates from our condition to consider life elsewhere (for example, life is more probable on exoplanets with liquid water and oxygen), so too can its logic and conclusions regarding extraterrestrial life offer lessons for humanity, Earth, and their joint future.

Our current sustainability challenge may pose a serious "bottleneck" to the species' long-term survival, through which we might or might not successfully pass. Life on distant planets is, in all likelihood, either much less or much more developed than we are.[2] If the latter, then it has presumably survived this filter and thrives without undermining its natural planetary foundations. What might such a sustainably prospering species' planet be like, and—more importantly here—how might the species interact with it?

Astrobiologist David Grinspoon distinguishes between what he calls the current proto-Anthropocene, in which humans' impacts on Earth systems are evident but largely unintended, with a potential mature Anthropocene, dominated by intentional impacts (Grinspoon, 2016). Humanity sits at a dilemma, he says, in which we are aware of our effects on the planet but cause them with neither clear objectives nor global self-control. Grinspoon asserts that intentionality will be necessary for our species' long-term survival and that the planet of any advanced extraterrestrial would emit signals of being managed. Importantly, he does not rule out the possibility of survival by lessening our global influence.

I do not prescribe a specific mix of intending and reducing humanity's effects on Earth systems. At the same time, the past half-century of research of and efforts toward sustainability have been dominated by reducing our impacts—and appropriately so. However, actual reductions seem insufficient, as suggested by increasing greenhouse gas emissions and biodiversity's continued decline, despite decades of international efforts on both fronts. Even though many observers may find ESIs unappealing, they deserve greater attention to help achieve sustainability and other goals. Much of this work falls within the natural sciences. Establishing well-designed governance to mitigate and manage the associated serious social, political, and ethical challenges will require informed examination of ESIs as such. Ultimately, humanity's relationship with the natural world in the Anthropocene—the "human epoch"—may include both an awareness that we already intervene in Earth systems as well as a resolution to do so consciously and responsibly. We should prepare for this possibility accordingly.

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[2] Consider time scales. Humans have been significantly modifying Earth systems for about 12,000 years, merely 0.0003% of the 4 billion years that our planet has supported life and 0.00009% of the 14 billion years that the universe has existed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adger, W.N., Pulhin, J.M., Barnett, J., Dabelko, G.D., Hovelsrud, G.K., Levy, M., Oswald Spring, U., Vogel, C.H., 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, pp. 755–791.
Allenby, B., 1998. Earth systems engineering: the role of industrial ecology in an engineered world. J. Ind. Ecol. 2 (3), 73–93.
Allenby, B., 2000. Earth systems engineering and management. IEEE Technol. Soc. Mag. 19 (4), 10–24.
Allenby, B., 2005. Reconstructing Earth: Technology and Environment in the Age of Humans. Island Press, Washington.
Allenby, B.R., Sarewitz, D., 2011. The Techno-Human Condition. MIT Press, , Cambridge, MA.
Anderson, K., Peters, G., 2016. The trouble with negative emissions. Science 354 (6309), 182–183.
Babcock, H.M., 2019. The genie is out of the de-extinction bottle: a problem in risk regulation and regulatory gaps. Va. Environ. Law J. 37 (3), 170–206.
Barnhill-Dilling, S.K., Serr, M., Blondel, D.V., Godwin, J., 2019. Sustainability as a framework for considering gene drive mice for invasive rodent eradication. Sustainability 11 (5), 1334.
Barrett, S., 2007. Why cooperate? The Incentive to Supply Global Public Goods. Oxford University Press, Oxford.
Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., Mercure, J.-F., Pollitt, H., Holden, P.B., Edwards, N.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I.A., Hansen, J., Banwart, S.A., 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature 583 (7815), 242–248.
Bellamy, R., Healey, P., 2018. Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. Environ. Sci. Policy 83, 1–10.
Bennett, J.R., Maloney, R.F., Steeves, T.E., Brazill-Boast, J., Possingham, H.P., Seddon, P.J., 2017. Spending limited resources on de-extinction could lead to net biodiversity loss. Nat. Ecol. Evol. 1 (4), 1–4.
Biermann, F., 2007. Earth system governance as a crosscutting theme of global change research. Glob. Environ. Change 17 (3), 326–337.
Birnie, P., Boyle, A., Redgwell, C., 2009. International Law and the Environment, Third Edition. Oxford University Press, Oxford.
Brent, K., McGee, J., McDonald, J., Rohling, E.J., 2018. International law poses problems for negative emissions research. Nat. Clim. Change 8 (6), 451–453.
Brossard, D., Belluck, P., Gould, F., Wirz, C.D., 2019. Promises and perils of gene drives: navigating the communication of complex, post-normal science. Proc. Natl. Acad. Sci. 116 (16), 7692–7697.
Browning, H., 2018. Won't somebody please think of the mammoths? De-extinction and animal welfare. J. Agric. Environ. Ethics 31 (6), 785–803.
Brownsword, R., Goodwin, M., 2012. Law and the Technologies of the Twenty-First Century: Text and Materials. Cambridge University Press, Cambridge, UK.
Burch, S., Gupta, A., Inoue, C.Y.A., Kalfagianni, A., Persson, Å., Gerlak, A.K., Ishii, A., Patterson, J., Pickering, J., Scobie, M., Van der Heijden, J., Vervoort, J., Adler, C., Bloomfield, M., Djalante, R., Dryzek, J., Galaz, V., Gordon, C., Harmon, R., Jinnah, S., Kim, R.E., Olsson, L., Van Leeuwen, J., Ramasar, V., Wapner, P., Zondervan, R., 2019. New directions in Earth system governance research. Earth Syst. Govern. 1, 100006.
Callies, D.E., 2019a. The ethical landscape of gene drive research. Bioethics 33 (9), 1091–1097.
Callies, D.E., 2019b. The slippery slope argument against geoengineering research. J. Appl. Philos. 36 (4), 675–687.
Callies, D.E., 2019c. Climate Engineering: a Normative Perspective. Lexington Books, Lanham, MD.
Carr, W.A., Preston, C.J., Yung, L., Szerszynski, B., Keith, D.W., Mercer, A.M., 2013. Public engagement on solar radiation management and why it needs to happen now. Clim. Change 121 (3), 567–577.
Clark, W.C., 1987. Sustainable development of the biosphere: themes for a research program. In: Munn, R.E., Clark, W.C. (Eds.), Sustainable Development of the Biosphere, editors. Cambridge University Press, Cambridge, UK, pp. 5–48.
Collingridge, D., 1982. The Social Control of Technology. Continuum International, London.
Convention on Biological Diversity, Secretariat, 2015. Synthetic Biology. Secretariat of the Convention on Biological Diversity. Montreal.
Corlett, R.T., 2017. A bigger toolbox: biotechnology in biodiversity conservation. Trends Biotechnol. 35 (1), 55–65.
Crookes, W., 1899. The Wheat Problem. John Murray, London.
Dave, R., Saint-Laurent, C., Murray, L., Antunes Daldegan, G., Brouwer, R., de Mattos Scaramuzza, C.A., Raes, L., Simonit, S., Catapan, M., Contreras, G.G., Ndoli, A., Karangwa, C., Perera, N., Hingorani, S., Pearson, T., 2018. Second Bonn Challenge Progress Report: Application of the Barometer in 2018. IUCN, Gland, Switzerland.
DeFries, R.S., Ellis, E.C., Chapin, F.S., Matson, P.A., Turner, B.L., Agrawal, A., Crutzen, P.J., Field, C., Gleick, P., Kareiva, P.M., Lambin, E., Liverman, D., Ostrom, E., Sanchez, P.A., Syvitski, J., 2012. Planetary opportunities: a social contract for global change science to contribute to a sustainable future. Bioscience 62 (6), 603–606.
Dryzek, J.S., 2016. Institutions for the Anthropocene: governance in a changing Earth system. Br. J. Polit. Sci. 46 (4), 937–956.
Dunlap, R.E., Liere, K.D.V., Mertig, A.G., Jones, R.E., 2000. New trends in measuring environmental attitudes: measuring endorsement of the new ecological paradigm: a revised NEP scale. J. Soc. Issues 56 (3), 425–442.
Dykema, J.A., Keith, D.W., Anderson, J.G., Weisenstein, D., 2014. Stratospheric controlled perturbation experiment: a small-scale experiment to improve understanding of the risks of solar geoengineering. Philos. Trans. R. Soc. A 372 (2031), 20140059.
Esvelt, K.M., 2017. Rules for sculpting ecosystems: gene drives and responsive science. In: Braverman, I. (Ed.), Gene Editing, Law, and the Environment: Life Beyond the Human. Routledge, Abingdon, UK and New York, pp. 35–52.
Esvelt, K.M., Gemmell, N.J., 2017. Conservation demands safe gene drive. PLoS Biol. 15 (11), e2003850.
Evans, B.R., Kotsakiozi, P., Costa-da-Silva, A.L., Ioshino, R.S., Garziera, L., Pedrosa, M.C., Malavasi, A., Virginio, J.F., Capurro, M.L., Powell, J.R., 2019. Transgenic *Aedes aegypti* mosquitoes transfer genes into a natural population. Sci. Rep. 9 (1), 1–6.
Faber, M., Manstetten, R., Proops, J.L.R., 1992. Humankind and the environment: an anatomy of surprise and ignorance. Environ. Values 1 (3), 217–241.
Fidelman, P., McGrath, C., Newlands, M., Dobbs, K., Jago, B., Hussey, K., 2019. Regulatory implications of coral reef restoration and adaptation under a changing climate. Environ. Sci. Policy 100, 221–229.

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S.R., Chapin, F.S., Seto, K.C., Weber, E.U., Crona, B.I., Daily, G.C., Dasgupta, P., Gaffney, O., Gordon, L.J., Hoff, H., Levin, S.A., Lubchenco, J., Steffen, W., Walker, B.H., 2021. Our future in the Anthropocene biosphere. Ambio 50 (4), 834–869.
Foxon, T.J., 2014. Technological Lock-in and the Role of Innovation. Handbook of Sustainable Development, Edward Elgar, Cheltenham, UK, pp. 304–316.
Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quere, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Change 4 (10), 850–853.
Galaz, V., 2014. Global Environmental Governance, Technology and Politics: the Anthropocene Gap. Edward Elgar, Cheltenham, UK.
Gambhir, A., Tavoni, M., 2019. Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation. One Earth 1 (4), 405–409.
Gasparini, B., McGraw, Z., Storelvmo, T., Lohmann, U., 2020. Storelvmo, T., Lohmann, U., 2020. To What Extent can Cirrus Cloud Seeding Counteract Global Warming? Environ. Res. Lett. 15, 054002.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31 (9), 1257–1274.
George, D.R., Kuiken, T., Delborne, J.A., 2019. Articulating 'free, prior and informed consent' (FPIC) for engineered gene drives. Proc. R. Soc. B 286 (1917), 20191484.
Godwin, J., Serr, M., Barnhill-Dilling, S.K., Blondel, D.V., Brown, P.R., Campbell, K., Delborne, J., Lloyd, A.L., Oh, K.P., Prowse, T.A.A., Saah, R., Thomas, P., 2019. Rodent gene drives for conservation: opportunities and data needs. Proc. R. Soc. B 286 (1914), 20191606.
Graham, J.D., Wiener, J.B., 1995. Risk vs. Risk: Tradeoffs in Protecting Health and the Environment. Harvard University Press, Cambridge, MA.
Greely, H.T., 2017. Is de-extinction special? Hastings Cent. Rep. 47 (S2), S30–S36.
Grinspoon, D., 2016. Earth in Human Hands: Shaping Our Planet's Future. Grand Central Publishing, New York and Boston.
Grunewald, S., 2019. CRISPR's creatures: protecting wildlife in the age of genomic editing. UCLA J. Environ. Law and Policy 37 (1), 1–57.
Gunderson, L., Light, S.S., 2006. Adaptive management and adaptive governance in the Everglades ecosystem. Policy Sci. 39 (4), 323–334.
Gupta, A., Möller, I., 2019. De facto governance: how authoritative assessments construct climate engineering as an object of governance. Environ. Polit. 28 (3), 480–501.
Guston, D.H., 2014. Understanding 'anticipatory governance. Soc. Stud. Sci. 44 (2), 218–242.
Gyngell, C., Savulescu, J., 2017. Promoting biodiversity. Philos. Technol. 30 (4), 413–426.
Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., Van Vuuren, D.P., Huijbregts, M.a.J., 2020. The climate change mitigation potential of bioenergy with carbon capture and storage. Nat. Clim. Change 10, 1023–1029.
Harding, A.R., Ricke, K., Heyen, D., MacMartin, D.G., Moreno-Cruz, J., 2020. Climate econometric models indicate solar geoengineering would reduce inter-country income inequality. Nat. Commun. 11 (1), 1–9.
Hayes, K.R., Hosack, G.R., Dana, G.V., Foster, S.D., Ford, J.H., Thresher, R., Ickowicz, A., Peel, D., Tizard, M., De Barro, P., Strive, T., Dambacher, J.M., 2018. Identifying and detecting potentially adverse ecological outcomes associated with the release of gene-drive modified organisms. J. Responsib. Innov. 5 (S1), S139–S158.
Head, B.W., Alford, J., 2015. Wicked problems: implications for public policy and management. Admin. Soc. 47 (6), 711–739.
Hoeksema, R.J., 2007. Three stages in the history of land reclamation in the Netherlands. Irrig. Drain. 56 (S1), S113–S126.
Holling, C.S., 1996. Engineering resilience versus ecological resilienc. Engineering Within Ecological Constraints. National Academies Press, Washington, pp. 31–43.
Horton, J.B., Keith, D.W., 2019. Multilateral parametric climate risk insurance: a tool to facilitate agreement about deployment of solar geoengineering? Clim. Policy 19 (7), 820–826.
Institute of Medicine, National Academy of Sciences, and National Academy of Engineering, 1992. Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. National Academy Press, Washington.
International Union for Conservation of Nature, Species Survival Commission. 2016. Guiding Principles on Creating Proxies of Extinct Species for Conservation Benefit.
IPCC, 2018. Global Warming of 1.5°C. Intergovernmental Panel on Climate Change.
India Today. 2019. Kaleshwaram Lift Irrigation Project. https://www.indiatoday.in/education-today/gk-current-affairs/story/kaleshwaram-lift-irrigation-project-facts-worlds-largest-multipurpose-lift-irrigation-project-1553474-2019-06-21.
Irvine, P.J., Keith, D.W., 2020. Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards. Environ. Res. Lett. 15 (4), 044011.
Jebari, J., Andrews, T.M., Aquila, V., Beckage, B., Belaia, M., Clifford, M., Fuhrman, J., Keller, D.P., Mach, K.J., Morrow, D.R., Raimi, K.T., Visioni, D., Nicholson, S., Trisos, C.H., 2021. From moral hazard to risk-response feedback, 33. Clim. Risk Manag, 100324.
Jinnah, S., Morrow, D., Nicholson, S., 2021. Splitting climate engineering governance: how problem structure shapes institutional design. Glob. Policy 12 (S1), 8–19.
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, 2019. High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques. International Maritime Organization, London.
Jones, M.S., Delborne, J.A., Elsensohn, J., Mitchell, P.D., Brown, Z.S., 2019. Does the U.S. public support using gene drives in agriculture? And what do they want to know? Sci. Adv. 5 (9), eaau8462.
Jordan, W.R., Lubick, G.M., 2011. Making Nature Whole: a History of Ecological Restoration. Island Press, Washington, Covelo, and London.
Karp, D.S., Mendenhall, C.D., Callaway, E., Frishkoff, L.O., Kareiva, P.M., Ehrlich, P.R., Daily, G.C., 2015. Confronting and resolving competing values behind conservation objectives. Proc. Natl. Acad. Sci. 112 (35), 11132–11137.
Kasperbauer, T.J., 2017. Should we bring back the passenger pigeon? The ethics of de-extinction. Ethics Policy Environ. 20 (1), 1–14.
Kohl, P.A., Brossard, D., Scheufele, D.A., Xenos, M.A., 2019. Public views about editing genes in wildlife for conservation. Conserv. Biol. 33 (6), 1286–1295.
Kolbert, E., 2021. Under a White Sky: the Nature of the Future. Crown, New York.
Lasswell, H.D., 1936. Politics: Who Gets What, When, How. McGraw-Hill, New York.
Leitschuh, C.M., Kanavy, D., Backus, G.A., Valdez, R.X., Serr, M., Pitts, E.A., Threadgill, D., Godwin, J., 2018. Developing gene drive technologies to eradicate invasive rodents from islands. J. Responsib. Innov. 5 (S1), S121–S138.
Lenzi, D., 2018. The ethics of negative emissions. Glob. Sustainab. 1, e7.
Lin, A.C., 2018. Carbon dioxide removal after Paris. Ecol. Law Q. 45 (3), 533–582.
Lin, A.C., 2020. Avoiding lock-in of solar geoengineering. North. Ky. Law Rev. 47 (2), 139–154.
Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C.L., Schneider, S.H., Ostrom, E., Pell, A.N., Lubchenco, J., Taylor, W.W., Ouyang, Z., Deadman, P., Kratz, T., Provencher, W., 2007. Coupled human and natural systems. AMBIO 36 (8), 639–649.
Lorimer, J., Driessen, C., 2014. Wild experiments at the Oostvaardersplassen: rethinking environmentalism in the Anthropocene. Trans. Inst. Br. Geogr. 39 (2), 169–181.
Mandel, G.N., 2009. Regulating emerging technologies. Law Innov. Technol. 1 (1), 75–92.
Mann, C.C., 2019. The Wizard and the Prophet: Science and the Future of Our Planet. Picador, London.
Marchant, G.E., Abbot, K.W., Allenby, B., 2013. Innovative Governance Models for Emerging Technologies. Edward Elgar, Cheltenham, UK.
Markusson, N., McLaren, D., Tyfield, D., 2018. Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). Glob. Sustain. 1, e10.
Marshall, R.B., 1920. Irrigation of Twelve Million Acres in the Valley of California. California State Irrigation Association, Sacramento.
Mitchell, P.D., Brown, Z., McRoberts, N., 2018. Economic issues to consider for gene drives. J. Responsib. Innov. 5 (S1), S180–S202.
Mitsch, W.J., 2017. Solving Lake Erie's harmful algal blooms by restoring the Great Black Swamp in Ohio. Ecol. Eng. 108 (B), 406–413.
Moe, E., Røttereng, J.-K.S., 2018. The post-carbon society: rethinking the international governance of negative emissions. Energy Res. Soc. Sci. 44, 199–208.

Moore, B., Underdal, A., Lemke, P., and Loreau, M.. 2001. Amsterdam declaration on Earth system science. http://www.igbp.net/about/history/2001amsterdamdeclarationonearthsystemscience.4.1b8ae20512db692f2a680001312.html.
Morrow, D.R., 2020. A mission-driven research program on solar geoengineering could promote justice and legitimacy. Crit. Rev. Int. Soc. Polit. Philos. 23 (20), 618–640.
Moses, L.B., 2007. Recurring dilemmas: the law's race to keep up with technological change, 2nd edition. Uni. Ill. J. Law Tech. Pol., pp. 239–285
NASA Astrobiology Institute. 2018, July 24. About NAI. https://astrobiology.nasa.gov/nai/about/.
National Academies of Sciences, Engineering, and Medicine, 2016. Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values. National Academies Press, Washington.
National Academies of Sciences, Engineering, and Medicine, 2018. Biodefense in the Age of Synthetic Biology. National Academies Press, Washington.
National Academies of Sciences, Engineering, and Medicine, 2019. Forest Health and Biotechnology: Possibilities and Considerations. National Academies Press, Washington.
National Academies of Sciences, Engineering, and Medicine, 2021. Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. National Academies Press, Washington.
Noble, C., Adlam, B., Church, G.M., Esvelt, K.M., Nowak, M.A., 2018. Current CRISPR gene drive systems are likely to be highly invasive in wild populations. eLife 7, e33423.
Novak, B.J., 2018. De-extinction. Genes 9 (11), 548.
Omori, M., 2019. Coral restoration research and technical developments: what we have learned so far. Mar. Biol. Res. 15 (7), 377–409.
Pollack, M.A., Shaffer, G.C., 2009. When Cooperation Fails: the International Law and Politics of Genetically Modified Foods. Oxford University Press, Oxford.
Pozo, C., Galán-Martín, A., Reiner, D., MacDowell, N., Guillén-Gosálbez, G., 2020. Equity in allocating carbon dioxide removal quotas. Nature Clim. Change, pp. 640–646.
Preston, C.J., 2016. Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene. Rowman & Littlefield, Lanham, MD.
Rauwald, K.S., Moore, C.F., 2002. Environmental attitudes as predictors of policy support across three countries. Environ. Behav. 34 (6), 709–739.
Ravetz, J.R., 1999. What is post-normal science. Futures 31 (7), 647–653.
Redford, K.H., Brooks, T.M., Macfarlane, N.B.W., Adams, J.S., 2019. Genetic Frontiers for Conservation: an Assessment of Synthetic Biology and Biodiversity Conservation. IUCN, Gland, Switzerland.
Reynolds, J., 2015. A critical examination of the climate engineering moral hazard and risk compensation concern. Anthropocene Rev. 2 (2), 174–191.
Reynolds, J.L., 2018. International law. In: Gerrard, M.B., Hester, T.D. (Eds.), Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal. Cambridge University Press, Cambridge, UK, pp. 57–153.
Reynolds, J.L., 2019. The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene. Cambridge University Press, Cambridge, UK.
Reynolds, J.L., 2020. Governing new biotechnologies for biodiversity conservation: gene drives, international law, and emerging politics. Glob. Environ. Polit. 20 (3), 28–48.
Reynolds, J.L., 2021. Engineering biological diversity: the international governance of synthetic biology, gene drives, and de-extinction for conservation. Curr. Opin. Environ. Sustain. 49, 1–6.
Reynolds, J.L., Contreras, J.L., Sarnoff, J.D., 2018. Intellectual property policies for solar geoengineering. Wiley Interdiscip. Rev. Clim. Change 9 (2), e512.
Reynolds, J.L., Parson, E.A., 2020. Nonstate Governance of Solar Geoengineering Research. Clim. Change 160, 323–343.
Ridge, J.T., Johnston, D.W., 2020. Unoccupied Aircraft Systems (UAS) for Marine Ecosystem Restoration, 7. Frontiers in Marine Science.
Rode, N.O., Estoup, A., Bourguet, D., Courtier-Orgogozo, V., Débarre, F., 2019. Population management using gene drive: molecular design, models of spread dynamics and assessment of ecological risks. Conserv. Genet. 20, 671–690.
Sandler, R., 2020. The ethics of genetic engineering and gene drives in conservation. Conserv. Biol. 34 (2), 378–385.
Schneider, S.H., 2001. Earth systems engineering and management. Nature 409, 417–420.
Shelton, A.M., Long, S.J., Walker, A.S., Bolton, M., Collins, H.L., Revuelta, L., Johnson, L.M., Morrison, N.I., 2020. First field release of a genetically engineered, self-limiting agricultural pest insect: evaluating its potential for future crop protection. Front. Bioeng. Biotechnol. 7, 482.
Singh, J.A., 2019. Informed consent and community engagement in open field research: lessons for gene drive science. BMC Med. Ethics 20 (1), 54.
Sjöberg, L., 2004. Principles of risk perception applied to gene technology. EMBO Rep. 5 (S1), S47–S51.
Smil, V., 2004. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT Press, Cambridge, MA.
Smith, W., 2020. The cost of stratospheric aerosol injection through 2100. Environ. Res. Lett. 15 (11), 114004.
Socolow, R.H., 1999. Nitrogen management and the future of food: lessons from the management of energy and carbon. Proc. Natl. Acad. Sci. 96 (11), 6001–6008.
Steeves, T.E., Johnson, J.A., Hale, M.L., 2017. Maximising evolutionary potential in functional proxies for extinct species: a conservation genetic perspective on de-extinction. Funct. Ecol. 31 (5), 1032–1040.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855.
Stjern, C.W., Muri, H., Ahlm, L., Boucher, O., Cole, J.N.S., Ji, D., Jones, A., Haywood, J., Kravitz, B., Lenton, A., Moore, J.C., Niemeier, U., Phipps, S.J., Schmidt, H., Watanabe, S., Kristjánsson, J.E., 2018. Response to marine cloud brightening in a multi-model ensemble. Atmos. Chem. Phys. 18 (2), 621–634.
Strong, A., Chisholm, S., Miller, C., Cullen, J., 2009. Ocean fertilization: time to move on. Nature 461 (7262), 347–348.
Sunstein, C.R., 2005. Laws of Fear: Beyond the Precautionary Principle. Cambridge University Press, Cambridge, UK.
Surprise, K., 2020. Geopolitical ecology of solar geoengineering: from a "logic of multilateralism" to logics of militarization. J. Polit. Ecol. 27 (1), 213–235.
Svoboda, T., 2017. The Ethics of Climate Engineering: Solar Radiation Management and Non-Ideal Justice. Routledge, London and New York.
Symons, J., 2019. Ecomodernism: Technology, Politics and the Climate Crisis. Polity Press, Medford, MA.
Thiele, L., 2020. Nature 4.0: assisted evolution, de-extinction and ecological restoration technologies. Glob. Environ. Polit. 20 (3), 9–27.
United Nations Environment Programme, 2020. Emissions Gap Report 2020. UNEP, Nairobi.
United Nations General Assembly. 2015. Transforming our world: the 2030 agenda for sustainable development (A/RES/70/1).
United States Bureau of the Census, 1975. Historical Statistics of the United States, Colonial Times to 1970. Government Printing Office, Washington.
Valdez, R.X., Kuzma, J., Cummings, C.L., Peterson, M.N., 2019. Anticipating risks, governance needs, and public perceptions of de-extinction. J. Responsib. Innov. 6 (2), 211–231.
Vale, T.R., 2013. Fire, Native Peoples, and the Natural Landscape. Island Press, Washington.
van Oppen, M.J.H., Gates, R.D., Blackall, L.L., Cantin, N., Chakravarti, L.J., Chan, W.Y., Cormick, C., Crean, A., Damjanovic, K., Epstein, H., Harrison, P.L., Jones, T.A., Miller, M., Pears, R.J., Peplow, L.M., Raftos, D.A., Schaffelke, B., Stewart, K., Torda, G., Wachenfeld, D., Weeks, A.R., Putnam, H.M., 2017. Shifting paradigms in restoration of the world's coral reefs. Glob. Change Biol. 23 (9), 3437–3448.
Vargas-Terán, M., Spradbery, J.P., Hofmann, H.C., Tweddle, N.E., 2021. Impact of screwworm eradication programmes using the sterile insect technique. In: Dyck, V. A., Hendrichs, J., Robinson, A.S. (Eds.), Sterile Insect Technique, Second edition. CRC Press, Boca Raton, FL, pp. 949–978.
Vitousek, P.M., Menge, D.N.L., Reed, S.C., Cleveland, C.C., 2013. Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems. Philos. Trans. R. Soc. B 368 (1621), 20130119.
Volokh, E., 2003. The mechanisms of the slippery slope. Harv. Law Rev. 116 (4), 1026–1137.
Wapner, P., 2014. The changing nature of nature: environmental politics in the Anthropocene. Glob. Environ. Polit. 14 (4), 36–54.
Weber, K.M., 2006. Foresight and adaptive planning as complementary elements in anticipatory policymaking: a conceptual and methodological approach. In: Voß, J.-P., Bauknecht, D., Kemp, R. (Eds.), Reflexive Governance for Sustainable Development. Edward Elgar, Cheltenham, UK, pp. 189–221.
Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., van der Leeuw, S., 2011. Tipping toward sustainability: emerging pathways of transformation. AMBIO 40 (7), 762–780.

Xia, L., Nowack, P.J., Tilmes, S., Robock, A., 2017. Impacts of stratospheric sulfate geoengineering on tropospheric ozone. Atmos. Chem. Phys. 17 (19), 11913–11928.
Zalasiewicz, J., Waters, C.N., Summerhayes, C.P., Wolfe, A.P., Barnosky, A.D., Cearreta, A., Crutzen, P., Ellis, E., Fairchild, I.J., Gałuszka, A., Haff, P., Hajdas, I., Head, M.J., Ivar do Sul, J.A., Jeandel, C., Leinfelder, R., McNeill, J.R., Neal, C., Odada, E., Oreskes, N., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., 2017. The working group on the Anthropocene: summary of evidence and interim recommendations. Anthropocene 19, 55–60.
Zomer, R.J., Trabucco, A., Bossio, D.A., Verchot, L.V., 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agric. Ecosyst. Environ. 126 (1), 67–80.