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OPINION

Look back lest you fail to mark the path ahead

Thomas E. Lovejoy

Center for Biodiversity and Sustainability, George Mason University, Fairfax, Virginia, USA

Correspondence
Thomas E. Lovejoy, Center for Biodiversity and Sustainability, George Mason University, Fairfax, VA 22030, USA.
Email: tlovejoy@gmu.edu

Societal Impact Statement

The need for immediate action to avoid further climate change and biodiversity loss is upon us. Plant scientists have the tools to initiate the first steps of this action, but we face challenges in ensuring that our message is transferred clearly and concisely to non-scientists. We must ensure that our research is rooted in reality, with reference to our current situation.

Summary

The devastating impacts of historical changes in atmospheric conditions demonstrate to scientists how precarious our current situation is, underscoring the need for immediate action to prevent further climate change. Humans are inherently adaptable creatures however, and we have so far managed to alter the planet to meet our own needs, cleverly exceeding natural limits and ignoring future consequences. We act as fugitive species, moving on to new resources rather than preventing their exhaustion, and attempting to treat the symptoms rather than the cause of ecological problems. To counteract this natural apathy in the face of relatively slow-burning but devastating issues such as climate change and biodiversity loss, we as scientists must highlight dramatic current issues, and put future problems in a contemporary context to demonstrate the urgency of these problems to non-scientists. Here, I discuss how we must make our arguments with reference to current reality, clearly, and unequivocally explaining the implications of our research, and proposing technological and ecological approaches to deal with the root cause of the issues we face.

KEYWORDS
Anthropocene, biodiversity, climate change, extinction, planetary boundaries

1 | INTRODUCTION

We practice our science in such a rapidly changing world that it is incumbent upon us, as citizen scientists, to communicate in ways that provide a clear context for the non-scientist. Consider the way we all so readily engage in academic debates in the scientific literature—sometimes the equivalent of intellectual box canyons of our own making—which readers beyond our immediate discipline find totally puzzling. As I put it to my students, how would you write a paper differently, knowing that non-scientists will read it?

I borrow my title for this piece from the Smithsonian Institution's “epigraph” for the Bicentennial of the United States: Look back lest you fail to mark the path ahead. I do so in part because the rate of change is itself changing so rapidly that if we do not write (or

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think!) carefully, it will be difficult for the future reader or listener to understand the real-world context and implications of our results. Given the human-generated environmental changes observed and expected, we now need to look both backwards and forwards at the same time (see Movie S1).

This is, in many senses, nothing new. It was crisply described by Pauly (1995) as "shifting baselines"; namely, that we—scientists and non-scientists alike—tend to accept the conditions from early in our lives as the "normal." In the future, it may be impossible to comprehend daily life in the Gay '90s (that is, the 1890s), the Street Wars of 1840's Manhattan, Astoria in Northwest USA, or that which I experienced in the Amazon in 1965, or even that such practices occurred. In the case of the fishery biologists in Pauly's classic paper, the subject was the condition of fish stocks. That concept has subsequently been wonderfully elaborated, in particular in the Island Press volume by Jackson, Alexander, and Sala (2011), and is fundamental to how we all should frame our results.

2 | HISTORICAL EXTINCTION EVENTS

The 1.5-billion-year-old seabed in the Pungalina-Seven Emu conservation area in Northern Australia is strewn with stromatolites, fossils created by colonies of blue-green cyanobacteria. I was given permission to bring one home as a teaching prop—what better example of an ecosystem service to highlight to students, given the way they oxygenated the atmosphere and enabled the origin of "higher life?" (Figure 1). A few weeks later, when preparing for the Centennial Meeting of the Ecological Society of America, I realized that what the cyanobacteria had been doing was filling the atmosphere with their own toxic waste, oxygen, while simultaneously drastically cooling the planet by reducing methane concentrations. In the process, they made themselves marginal, and presumably eliminated many other protists. Looking back—in this case to what I now think of as the "Lesson of the Stromatolites"—should therefore help us understand the imperative of avoiding the dangerous alteration of atmospheric composition.

This Great Oxygenation event is not included as one of the five major extinction events (Figure 2; six if one counts the current event that humans are precipitating), which are based primarily on the disappearance of hard-bodied species in the marine fossil record (in contrast to the current event, in which the terrestrial element has been more conspicuous). It probably should be counted, however, as it was an equivalent period of major planetary transformation.

There is a similar narrowness in the discussion of whether the Sixth Great Extinction is really underway. We already know that extinction rates are approaching 1,000 times the biological norm (Pimm et al., 2014), and that there has been a major and rapid destruction of most types of terrestrial habitat. So far, the impacts have been mostly on terrestrial species, although the changes in marine environments are multiple and vast; overfishing is ubiquitous, plastics have pervaded the oceans, and human action is changing the basic chemistry of seawater. Most recently, population losses and declines in terrestrial vertebrates have been detected at such a scale (Ceballos, Ehrlich, & Dirzo, 2017) that they presage a tsunami of extinction (Lovejoy, 2017). These are the early stages, but the full impact will be upon us in decades unless immediate action is taken. To do nothing is tantamount to disregarding the initial withdrawal of the ocean that preludes a tsunami, but there the analogy ends because we can in fact do a lot to halt and reverse the process. To argue that there is nothing equivalent to the major marine extinctions of the Ordovician–Silurian Extinction Event 439 million years ago, and that this therefore cannot qualify as a major extinction event, seems to beg the point: if we count the Great Oxygenation as an extinction event, how can it be argued that all extinction events have to be measured in the same way?

3 | BREACHING PLANETARY BOUNDARIES

The Planetary Boundaries (Rockström et al., 2009; Steffen et al., 2015; Figure 3) are an estimation of the environmental boundaries within which humans can safely operate, and represent an incredibly

FIGURE 1 Stromatolite fossil from Pungalina-Seven Emu Wildlife Sanctuary in Northern Territory Australia (Australia Wildlife Conservancy)

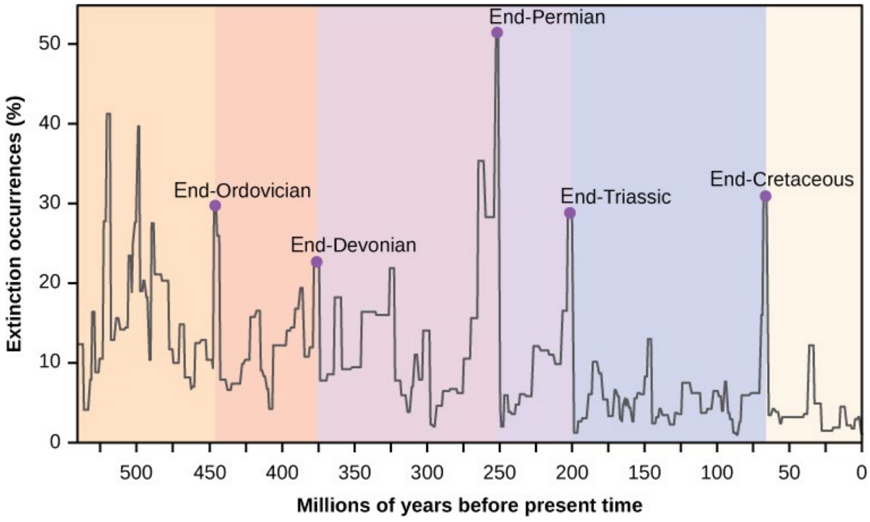

FIGURE 2 The five ancient mass extinctions in the fossil record. Image courtesy of CNX (OpenStax College, Biology, 2018)

important contribution to understanding our impact on the biosphere. They have received some technical critiques and corrections; however, dismissing them altogether is badly short-sighted. Some of their criticism (often from politicians) has stemmed from mistakenly viewing the boundaries as limits; they are not limits in the typical sense—asymptotes that cannot be exceeded without a flip to some major and different state—but they do represent the boundary conditions that facilitated the rise of human civilization. As such, it should give us serious pause that we have so clearly exceeded the boundaries of the carbon and nitrogen cycles, plus that which represents the diversity of life on Earth during the Holocene.

The nitrogen cycle boundary has been exceeded to a great degree by the overuse of nitrogen fertilizers and the combustion of fossil fuels, and it is quite clear that passing the boundary has already had hugely deleterious effects. The great dead zone at the mouth of the Mississippi River in the Gulf of Mexico, caused by nitrogen enrichment and subsequent algal blooms and oxygen depletion (Rabalais, Turner, & Wiseman, 2002), is not a solitary example; the number of dead zones in estuaries and coastal waters around the world has doubled every decade for 40 years (Diaz & Rosenberg, 2008), representing an unnecessary consequence of modern agriculture that reduces the productivity and biodiversity of all those coastal waters.

The extent to which Steffen and colleagues' 2015 analysis shows the breach of the climate boundary primarily as the distortion of the carbon cycle is, in my view, an underestimation, especially when considering the impact of climate change on biodiversity and biological systems (Lovejoy & Hannah, 2019). Even without such an

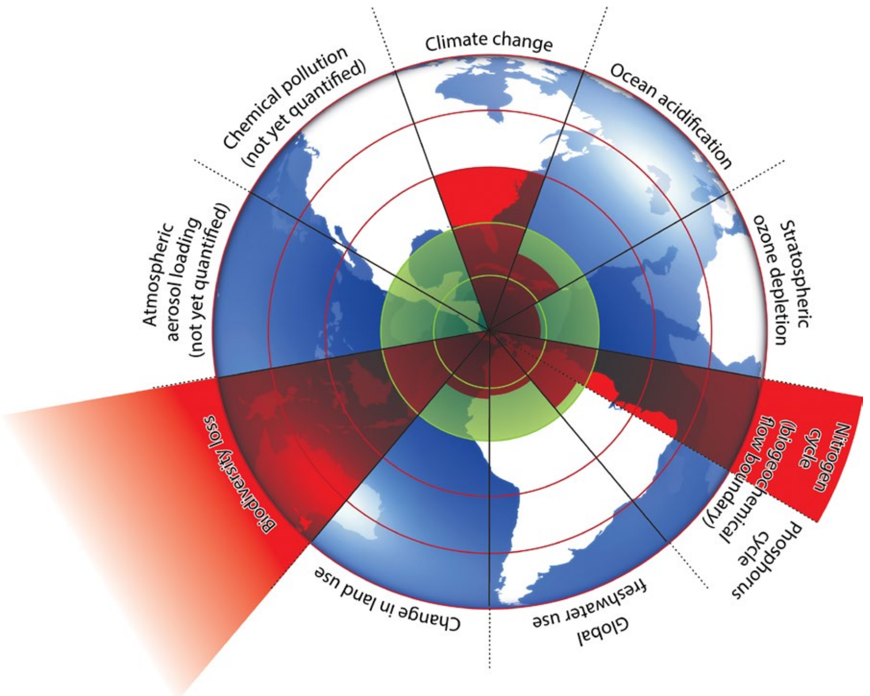

FIGURE 3 Planetary boundaries. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change, and the nitrogen cycle) have already been exceeded. Reproduced with permission from Rockström et al. (2009) [Colour figure can be viewed at wileyonlinelibrary.com]

adjustment, it has obviously exceeded the preindustrial "boundary," and the climate is clearly warming and changing in various ways. I am reminded of G. Evelyn Hutchinson's chilling comment at his Franklin Medal ceremony that he did hope the various things we were doing to the atmosphere would cancel each other out.

The consequences for sea level rise in the initial Intergovernmental Panel on Climate Change (IPCC) forecasts were extremely conservative, in part because of processes of international negotiation. While much of the debate centered around the rate of sea level rise, the endpoint was always obvious: the last time the planet was 2.0°C warmer (during the Eemian Stage, 150,000—115,000 years ago), the oceans were 4–6 m higher (Kopp, Simons, Mitrovica, Maloof, & Oppenheimer, 2009). Were we to stop at 2.0°C, the result is not in dispute; it is the rate of change that is unknown. The Paris Climate Agreement referred to an increase of 2.0°C or less, largely because 2.0°C was thought to be achievable, rather than having intrinsic merit; however, most of the debate about targets and timetables has not been anchored in that reality. It was the small island states, more vulnerable to sea level rise than most other nations, who helped enlighten large island states and awaken the seemingly oblivious continental states, most of whom have equally vulnerable coastlines. They succeeded, in part because the number of small island states is not trivial and the other nations fundamentally realize that it is not acceptable to eliminate another state by sea level rise. Consequently, there is now more emphasis on a target of 2.0°C *or less*, instead of just focusing on 2.0°C as if it were "safe." Unfortunately, far too many people and nations still throw around values of 2.0, 3.0, 4.0°C, or more, as if it had no more consequence than a torrid summer afternoon.

From any biological analysis, an increase of 2.0°C will be very bad for biodiversity (Lovejoy & Hannah, 2019). Today, at close to 1.0°C, the fingerprints of climate change on biodiversity are already ubiquitous, with changes observed in phenology and geographic distributions. Those are minor ripples in the fabric of life, but look back: they are trivial in comparison with those that took place during the postglacial periods, when each species moved at its own characteristic rate and direction, disassembling ecosystems. A major goal should therefore be to limit climate change to 1.5°C, where the biological management of the challenge might conceivably be achievable.

Abrupt change is already taking place. Tropical coral reefs are very sensitive to even brief periods of warmer water, which cause the fundamental partnership on which the entire ecosystem is based to collapse; the coral animal ejects the algal partner, causing bleaching events. From the immediate point of view of humanity, 5% of whom live within 100 m of a coral reef, it is irrelevant that coral animals are exploring cooler waters south of the Great Barrier Reef, even if we are encouraged by the survival prospects of these species. A similar abrupt change involves the dieback of the coniferous forests of western North America, from southern Alaska to southern Colorado. Problematic tree-killing beetles can overwinter more successfully, gaining an additional generation that tips the balance in their favor. These two examples suggest that climate and vegetation models will always be insensitive in projecting climate impacts because they cannot detect or represent the novel changes to idiosyncratic relationships between two (or a few) keystone species. Together with ocean acidification and the possibility of abrupt change within the climate system itself, these issues make a strong argument for dropping the use of 2.0°C as an acceptable target. Talk of 2.0°C should make our blood run cold.

4 | ADAPTABILITY BREEDS APATHY

Species such as beaver, which are so good at increasing the carrying capacity of their environment (by building dams and creating ponds in their case), look like amateurs compared with humans. Our adaptability makes it extremely difficult to determine how many people the Earth could support, a question that Joel Cohen struggled with in his 1995 book on the subject (Cohen, 1995). It has long been clear that human numbers and behavior are badly degrading our resource base. We have certainly vastly increased the capacity of the biosphere to support human numbers, first through agriculture, then through human settlements; however, we achieved this by ignoring limits, exceeding them through ingenuity and a psychology that tends to deny their reality. Sometimes that leads to unfortunate surprises; for example, in the American dustbowl, where nobody understood that the regional climate was dependent on vegetation cover until the damage was done. Likewise, we know that the Amazon makes half of its own rainfall, which requires a minimum forest cover of 80% (Lovejoy & Nobre, 2018); however, it is still vulnerable to short-term interests, which are oblivious or uncaring about anything other than immediate economic benefit.

In a sense, we tend to behave as a fugitive species, moving on when the local carrying capacity crashes beneath and behind us. The vast amount of degraded land in the world is testament to this. This strategy is absolutely not sustainable, and we should recognize that successful fugitive species move at a rate roughly equivalent to that at which the environment returns to its original state. Those who dream of terra-forming Mars or another planet to which humanity can adjourn after ruining Earth are guilty of the ultimate folly; this goal is simply energetically impossible except for some elite super-minority.

The same fugitive species mentality lurks in much of the thinking and dreaming about geo-engineering as a solution for climate change. Probably, the most profound statement on this came from the National Academy Committee, chaired by Marcia McNutt, which concluded that "geo-engineering" is an invalid term because it is only possible to engineer a system (in this case the biosphere–geosphere) that one can fully understand. The pressure to opt for geo-engineering grows as atmospheric CO_2 concentrations increase and as preventing a 1.5°C warming appears illusory. Some of the proposed solutions, such as injecting sulfate particles into the atmosphere to mimic the temporary effects of volcanic events, are designed to alter the albedo of the Earth; however, exploring the consequences of temporary sulfate increases from actual volcanic eruptions is important before undertaking such experiments. To the extent that these manipulations are global in scale, any unanticipated downsides will be too. Even if there are no detrimental effects, these solutions are only temporary, as the effects will end when the procedure ends, and the Earth's temperature will jump to where it would have been in the absence of such interventions. Such interventions could, however, be useful on a modest timescale, enabling us to address Arctic warming while other solutions are sought. Geo-engineering "solutions" also address only the symptom (temperature) rather than the cause, so they will do nothing for issues such as the problem of ocean acidification.

5 | THE SEARCH FOR SOLUTIONS

Interventions that lower atmospheric CO_2 concentrations actually deal with the cause of the problem; however, none have yet reached a promising scale. Carbon capture and storage is still largely in the experimental phase, while capturing CO_2 in smokestacks and converting it into useful products such as high-reflectance concrete is beneficial but limited in scale. It is perfectly possible that new products and manufacturing processes will be identified that can convert CO_2 into something of value; however, pulling it out of the atmosphere is much more expensive than from a chimney, where it is about 100 times more concentrated.

The potential contribution of ecosystem restoration is truly underestimated. The gross annual emissions resulting from forest destruction comprise about 30% of annual global emissions (Houghton & Nassikas, 2015), so eliminating that is vital, but look back: a vast amount of atmospheric carbon has come from the degradation and destruction of ecosystems over the last few centuries. The most recent estimate is that the amount of atmospheric CO_2 released when altering ecosystems is roughly equivalent to the amount which remains in those ecosystems (Erb et al., 2017). If restoration is undertaken at scale, 0.4–0.5°C of warming could be avoided by pulling that CO_2 from the atmosphere and converting it into living matter (Griscom et al., 2017; Lovejoy, 2014).

The most excessively exceeded planetary boundary is "biodiversity," which is not surprising because of the ways it can be affected, both directly by processes such as habitat destruction, but also indirectly by climate change and various forms of pollution. Biodiversity integrates all environmental problems because they all affect living systems—a principle demonstrated by Ruth Patrick in 1949 (Patrick, 1949; Patrick, 1977; Pye & Patrick, 1983).

6 | LOOK BACK AND MARK THE PATH AHEAD

We need to be able to understand the implications of global change in terms of the trajectory in which it has come. If a study contemplates a scenario in the quite distant future, which could be just 100 years hence given current human-driven rates, it is important to give the reader a point of reference in the present, otherwise it becomes difficult to ponder both the path ahead and the possible policy implications. The point is to provide the consumers of our science a real-world context, which is not always about looking back; for example, the increased growth rates of forests caused by elevated atmospheric CO_2 are important to understand because of the implications for the global carbon cycle. The effects can be seen in the incredibly biodiverse Amazon rainforest, but need to be put into context; for example, the climate is favoring the faster growth of lianas than of the trees themselves. The documented carbon uptake might be inserted into a climate model, but it needs the context that nutrient limitations, in this case of phosphorous, could make this a short-lived "benefit."

This article is not intended as an argument for stasis, for bringing environmental change to a dead halt. That certainly is not a practical option given the amount of change that has already taken place and the multiplicity and variety of the anticipated change; indeed, it probably never was, even for the less-disturbed ecosystems observed over the last two centuries. All ecologists, including Tansley, Hutchinson, Lindemann, Odum, and those who have followed, understood that ecosystems are dynamic. Instead, I wish to make the argument that our intellectual analyses and excursions should be tempered with points of reference anchored in reality. Otherwise, we will be forever trapped in shifting baselines, wandering unnecessarily into intellectual box canyons, leaving non-scientists confused as to the wise path ahead.

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