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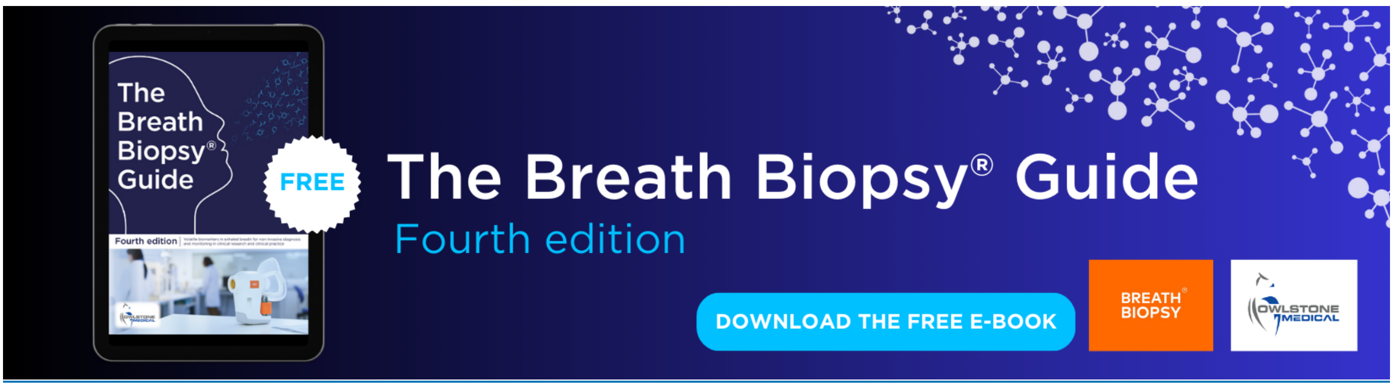
To cite this article: William J Ripple *et al* 2024 *Environ. Res. Lett.* **19** 021001



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RECEIVED
7 June 2023

REVISED
13 October 2023

ACCEPTED FOR PUBLICATION
20 October 2023

PUBLISHED
9 January 2024

PERSPECTIVE

An environmental and socially just climate mitigation pathway for a planet in peril

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Keywords: ecological overshoot, climate change, scenario modeling

Supplementary material for this article is available online

Climate change—a critical issue that many consider a major threat for life on Earth—is a symptom of ecological overshoot, long-term consumption and production patterns that lead to excessive and unsustainable environmental pressure. To address climate change, we must address these underlying causes and take steps towards sustainable living practices that prioritize the health of the biosphere and all its human and nonhuman inhabitants. Earlier compilations of anthropogenic environmental pressures have typically only considered the last few decades. Here, we put relevant variables into context for the last 500 years using a diverse and likely novel set of key data. Our long-term graphical account illustrates how humanity's collective demand for natural resources is greatly accelerating on multiple fronts. Furthermore, we display and examine an ambitious and commonly used climate mitigation scenario, and propose a holistic, restorative scenario be considered, which is inspired by existing scenarios (Van Vuuren *et al* 2017). Our proposed ecologically-grounded and socially just scenario requires long-term comprehensive changes that could be implemented using short-term incremental steps (radical incrementalism). It illustrates how humanity can mitigate converging crises and realize diverse co-benefits, including potentially increasing global biodiversity and social equity. We argue that strong social outcomes and global justice, as in the proposed scenario, should be given greater consideration in climate scenarios.

1. Vital signs data analysis

We compiled long-term historical data for variables related to human activities, land use, and the atmosphere from various sources (see supplemental methods). For each variable, we used data from 1500 CE (1500 AD), when available, to increase contextual awareness and clearly display recent trends. In addition to fossil fuel carbon dioxide (CO_2) emissions, three greenhouse gas concentrations, and surface temperature, we included human population, per-capita gross domestic product (GDP), three land use variables, vertebrate species abundance, and an equity variable (top 10% share of income). For most variables, we also obtained shared socioeconomic pathway (SSP) projections up to the year 2100 for the SSP1-1.9 pathway, which corresponds to low future emissions (see supplemental methods).

2. Historical trends

Unchecked growth of industrial production over the past two centuries has led to an unprecedented rise in energy consumption, with fossil fuels remaining the primary source of energy (figures 1(a)–(c)). This has led to a strong increase in greenhouse gas emissions. Furthermore, land use change, particularly deforestation (driven by agricultural land expansion and wood demand), has also been one of the major contributors to climate change (figures 1(d), (e) and (j)). Additionally, agricultural

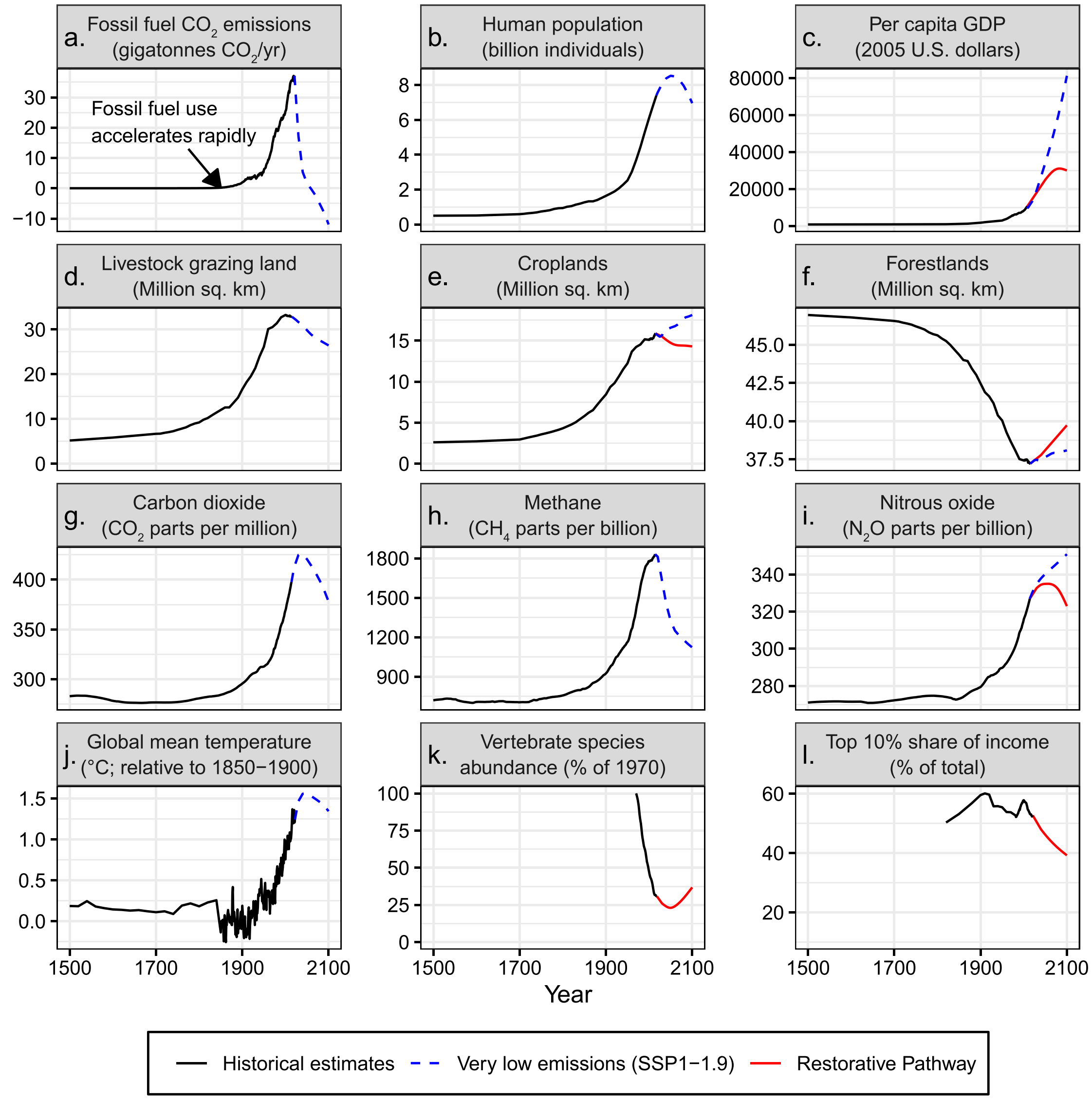

Figure 1. Visualizing a restorative pathway. Each panel shows a different planetary vital sign, including historical estimates and projections through 2100 under the SSP1-1.9 scenario, when available. Stylized projections for the proposed restorative pathway are only shown for cases where it likely differs substantially from SSP1-1.9; these projections are intended as a general qualitative overview of the pathway. All variables show a history of rapid change, often beginning around 1850 when fossil fuel use began to accelerate rapidly. See supplemental methods for sources and details on the variables.

practices such as livestock farming and fertilizer use on crops emit significant amounts of greenhouse gasses such as methane and nitrous oxide. The loss of forests and other natural ecosystems impacts biodiversity and also reduces the ability of the land to absorb and store carbon, exacerbating the problem.

The magnitudes of the changes since 1500 CE are enormous. For example, the world's forest lands declined by 21% (9.7 million km^2) while livestock grazing lands increased six-fold (27.7 million km^2) and crop lands increased six-fold (13.3 million km^2) (figures 1(d)–(f)). Changes in land use and other human pressures contributed to mean vertebrate species abundance (relative to 1970) declining by 69% (figure 1(k)). Taken together, our graphical results show a stark pattern comparable to the classic hockey stick pattern originally observed for global temperature (Mann 2021) for nearly all of our variables. Specifically, our results show a great escalation beginning around 1850 for most variables (figure 1). If combined with information on carrying capacity or planetary boundaries, these data could be used to explore the possibility that human demands on multiple fronts have greatly accelerated and may have approached or exceeded the biosphere's regenerative capacity (Steffen *et al* 2015, Rockström *et al* 2023). From a population, fossil fuel, greenhouse gasses, temperature, and land use perspective, the mid 19th century (~1850) stands out as a compelling choice among the potential starting points for the Anthropocene.

3. SSP1 climate mitigation scenario

As a future climate scenario under optimistic conditions we selected and graphed the SSP1 scenario in combination with stringent climate policy (SSP1-1.9) to the year 2100 which has a 'green growth' storyline that involves significant changes in energy production, land use, and other areas (Van Vuuren *et al* 2017). With this scenario, we see a bending of the curves toward a more sustainable direction for some variables as we move through the rest of this century (figure 1). This includes a projected downturn in human population (beginning around 2050), livestock grazing land, carbon dioxide, and methane, but per capita GDP, croplands, and nitrous oxide continue upward. Within SSP1-1.9, forest lands are projected to increase by ∼0.9 million km^2, and livestock production is expected to peak around 2050, but still remains ∼6% higher than current levels by 2100 (table S1).

In the SSP1-1.9 scenario, fossil fuel CO_2 emissions would be quickly slashed in combination with the strong reliance on carbon capture technology to provide net negative emissions of 5.5–12.0 Gt CO_2 yr^{-1} by 2100 (figure 1(a)). Negative emissions technologies are still in the very early stages of development (Martin-Roberts *et al* 2021). They currently capture some 0.045 Gt of CO_2—more than two orders of magnitude below the above target (IEA 2023)—and there are major uncertainties around their efficacy, scalability, and potential environmental and social impacts (Anderson and Peters 2016). Research should continue, but relying on major carbon removal strategies at this time may result in a false sense of security and delay the necessary actions to address climate change.

The SSP1 storyline assumes continuing economic growth (∼26% GDP/decade, figure 1(c)). It is an open question whether this is a desirable economic pathway. Some studies have shown that absolute decoupling is possible and in fact has already occurred historically (Le Quéré *et al* 2019). However, this trend would need to be sustained at higher rates of decarbonization over a long period and globally, so far, global carbon emissions continue to rise with increased economic activity (Hickel *et al* 2021). Moreover, there is also a debate on the desirability of income growth itself. High-income countries may not need continued economic growth, and it has been shown that positive social outcomes can occur without growth (Hickel *et al* 2021); but this subject may be controversial.

The SSP1-1.9 scenario also depicts an increase in both the area of croplands and corresponding increase in nitrous oxide emissions (figures 1(e) and (h)). Croplands are predicted to expand by at least ∼2.2 million km^2 by 2100 under this scenario. Any expansion of cropland will come at a great cost to the environment and biodiversity, as it often involves deforestation, soil degradation, and depletion of freshwater resources. Likewise, agriculture is the largest source of nitrous oxide emissions, mostly from nitrogen-based fertilizers and livestock manure, both of which release nitrous oxide during decomposition. There has been little research and a serious gap in global policy on nitrous oxide; it has been dangerously neglected despite its important and rising contribution to global heating (Nisbet *et al* 2021). The obvious remedy is to greatly expand mostly plant-based diets or develop laboratory meat (if it can scale up) to curb both the conversion of wildlands into croplands for livestock feed and the increases in nitrous oxide levels. Other work, however, has shown that by a more substantial transition to less meat-intensive diets it is possible to decrease both crop and livestock grazing land (Van Vuuren *et al* 2018, Willett *et al* 2019, Leclère *et al* 2020).

4. The 'Restorative' pathway

SSP1-1.9 presents a useful and detailed depiction of green growth, but we believe there is value in comparing it to other, sustainability-focused storylines. Therefore, we call for the development of a new restorative pathway scenario that would go further for sustainability and equity than the current SSP1. It would involve significantly bending not just some, but all of the curves in figure 1 with a minimal need to rely on carbon capture technologies. The scenario would also focus on reducing the consumption of primary resources to keep environmental pressures within planetary boundaries. The restorative pathway would represent a more equitable and resilient world with a focus on nature preservation with vast reserves as a natural climate solution; post-growth economics; societal well-being and quality of life; equality and high levels of education for girls and women resulting in low fertility rates with higher standards of living; more efficient crop fertilizer use; a diet shift with major reductions in meat production; and a rapid transition towards renewable energy (figures 1 and S1).

The restorative pathway builds on the current SSP1 and other sustainability scenarios (e.g. Van Vuuren *et al* 2018, Grubler *et al* 2018, Leclère *et al* 2020, Hickel *et al* 2021, Soergel *et al* 2021) with a positive vision for the future, where production prioritizes human needs and inequality is drastically reduced. In contrast to SSP1, this proposed scenario could include greater convergence of per-capita GDP, meat consumption, and energy use throughout the world (Hickel *et al* 2021). This would ensure that for both the global north and south, energy and resource consumption moves toward equal per capita levels, thus promoting socio-economic justice, universal human well-being, and the preservation of ecological capital (figure 1 (l); Millward-Hopkins and Oswald 2023). By prioritizing large-scale societal

Table 1. Important causal relationships in the restorative pathway. Table rows describe how sets of key variables in the restorative pathway are generally consistent with each other and the scientific literature. 'Projected changes' indicate changes in the key variables outlined for this scenario. 'Contributing factors in the Restorative Pathway' describes changes in other variables that are consistent with the projected change as described in the 'evidence for cross-factor consistency' column. The list is not intended to be exhaustive, and many other factors likely affect the projected changes. Note that references may not fully cover all associated relationships. See supplementary discussion for details and additional limitations.

Contributing factors in the restorative pathway	Projected changes	Evidence for cross-factor consistency
Equitable economic policies that address overconsumption and support convergence in resource use (figure 1(l))	Per capita GDP stabilizes over time (figure 1(c))	Reducing consumption by the wealthy can have a substantial impact on GDP trends (Hickel *et al* 2021)
Equality and better education for girls and women	Fertility rates and human population size decrease (figure 1(b))	Better education for girls and young women along with other rights-based policies could reduce population growth rates (Dodson *et al* 2020)
Human population size decreases (figure 1(b)), per capita GDP stabilizes over time (figure 1(c)), plant-based diets become more prevalent	Fossil fuel emissions (figure 1(a)), croplands (figure 1(e)), meat production (figure S1), and livestock grazing land (figure 1(d)) decrease; forestlands (figure 1(f)) increase	Reductions in demands for resources can in turn reduce fossil fuel emissions and land area required for human activities (Dodson *et al* 2020, Ripple *et al* 2022)
Fossil fuel emissions (figure 1(a)), livestock grazing land (figure 1(d)), croplands (figure 1(e)), and meat production decrease (figure S1); forestlands increase; farming practices improve	Carbon dioxide (figure 1(g)), methane (figure 1(h)), and nitrous oxide (figure 1(i)) concentrations decrease	Reducing fossil fuel emissions, more efficient land use, and nature conservation can reduce greenhouse gas concentrations (Van Vuuren *et al* 2017, Nisbet *et al* 2021)
Carbon dioxide (figure 1(g)), methane (figure 1(h)), and nitrous oxide (figure 1(i)) concentration decrease	Global mean temperature decreases (figure 1(j))	Reducing greenhouse gas concentrations can reduce the rate of global warming (Steffen *et al* 2015, Ripple *et al* 2022)
Forestlands increase (figure 1(f)), livestock grazing lands (figure 1(d)), meat production (figure S1), and croplands (figure 1(e)) decrease, human population size decreases (figure 1(b)), per capita GDP growth slows (figure 1(c)), temperature decreases (figure 1(j))	Vertebrate species abundance increases (figure 1(k))	Biodiversity can benefit from a wide range of anthropogenic actions (Leclère *et al* 2020, Kuhnhenn *et al* 2020)

change, the proposed pathway could limit warming much more effectively than pathways that support growing consumption in wealthy nations (Kuhnhenn *et al* 2020). The pathway would also feature the use of more efficient farming practices to reduce greenhouse gas emissions (table 1).

The internal consistency of scenario model results can be assessed by determining whether projections and relationships between projections agree with existing theories, data, or empirical analysis (Jiang 2014). The restorative pathway appears to be internally consistent based on simple qualitative checks of the general relationships between projections (table 1; see supplemental discussion). Thus, the restorative pathway proposal could potentially serve as an intermediate step toward the rigorous formulation and simulation of a holistic climate mitigation scenario. An important next step would be to conduct a joint modeling assessment to rigorously assess the plausibility and internal consistency of the stylized projections for individual variables (figures 1 and S1) and produce plausible and realistic modeled estimates. Such an assessment could help quantify how the restorative pathway and SSP1 differ in key dimensions, including GDP, cropland area, forestland area, and nitrous oxide emissions.

5. Final words

To effectively address climate change, it is essential for governments to take holistic action that prioritizes equity and social justice. However, the situation presents a challenge as the current viewpoint is rooted in continued growth, which limits consideration of different perspectives, including those of diverse and vulnerable poplations. The climate crisis requires immediate action, but a long-term perspective is also important given the magnitude of the necessary changes and the ultimate goal of cooling our planet back down to a safe level.

As the world grapples with the urgent need to address the climate crisis, it is crucial for researchers to combine ecological, social, and climate domains in future scenarios, so that the cross-linkages become apparent. While technology no doubt represents a critical part of the solution, its potentially unlimited and extensive use could create new problems given that the planet's resources are finite and already under tremendous strain. Ecological overshoot or the overexploitation of the Earth is the cause of multiple environmental and social crises, and policies should focus on addressing this issue rather than simply treating the symptoms. As human demand continues to exceed planetary boundaries and the regenerative capacity of nature, we are at increased risk from not only climate change, but a confluence of crises, including biodiversity loss, species extinctions, freshwater shortage, food scarcity, civil unrest, international wars, pollution, and zoonotic diseases and more pandemics (Guterres 2023, Rockström *et al* 2023). Mitigating overexploitation and these crises will require global cooperation to address inequality and injustice.

Adding a restorative pathway-like scenario to climate models would provide a more comprehensive picture of what could lie ahead and help decision-makers prepare for a sustainable future that may look vastly different from the current paradigm of population and consumption growth. We understand that our proposed scenario may be a major challenge to implement (like SSP1), considering trends in emissions, a lack of political will and widespread social denial (Norgaard 2011), but only if something like the restorative pathway is included as an input to climate models, will we be able to debate its merits. The plausibility of the SSPs and restorative pathway should be systematically considered (see supplemental discussion on scenario likelihood). Political and popular support for the restorative pathway could be achieved through radical incrementalism—a framework based on achieving radical or significant change by making a series of smaller changes and continuously evaluating their effectiveness (Halpern and Mason 2015). In addition to curbing fossil fuel emissions, we need small incremental steps towards bending all the curves in figure 1.

As we witness the goal of the Paris agreement slipping away, avoiding even a tenth of a degree of future global heating is still of utmost importance. It is time to acknowledge that business-as-usual for a planet in peril is no longer viable and that we must start planning for a world that prioritizes conservation, sustainability, resilience, and equity. Ultimately, addressing climate change will require a coordinated effort to not only reduce emissions and support vulnerable communities, but also make incremental long-term changes for humanity and other life on Earth.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

We thank David Johns for reviewing a draft of the paper and providing helpful comments. Roger Worthington provided partial funding for this project.

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