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Short communication

The impact pulse and restoration curves: Going beyond mitigation and stabilization

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ABSTRACT

Mitigation measures proposed as a response to the carbon and climate problem represent only the first half of a complete solution. Proactively repairing the damage through restoration represents the remaining half, which must entail the capture and storage of trillions of tons of carbon dioxide (CO_2). Given that the time required for natural processes to restore the concentration of atmospheric CO_2 to its baseline level is on the order of centuries, timely removal must involve carbon dioxide removal (CDR) geoengineering. Idealized impact and restoration scenarios, which build upon earlier conceptions of stabilization wedges, are proposed as conceptual tools with which to frame policy responses. These scenarios suggest that climate policy must weigh tradeoffs between nearer-term mitigation measures and longer-term CDR interventions. The tradeoffs depend on whether we wish to minimize the magnitude (peak CO_2 concentration) or duration (time to reach pre-industrial CO_2 levels) of the impact. Generalizing beyond the specific example of climate change, more rigorous consideration of technology-dependent impact and restoration scenarios can help provide a much-needed reality check for both environmental alarmism and technological optimism. This check is important as humanity transitions from the unintentional Anthropocene to the intentional Anthropocene over the course of this century. The prospect of the intentional Anthropocene also raises important ethical questions about the human-nature relationship.

1. Introduction

In 2004, Stephen Pacala and Robert Socolow published a widely-cited article entitled “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies” (2004). This paper provided a simple idealized framework for conceptualizing mitigation strategies with which to halt the annual growth of carbon dioxide (CO_2) emissions by mid-century. The authors proposed that existing strategies and technology, when combined, could allow humanity to “solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do,” and that a useful way to visualize this solution was as a “stabilization triangle” composed of “wedges” (2004, p. 968). Each wedge represents an activity that can achieve a one-gigaton reduction in annual fossil fuel emissions of carbon (1GtC/year, or 3.67GtCO_2/year) by mid-century.

The Pacala and Socolow conception of stabilization wedges is a high-profile example of how the climate change discourse may be shaped by clear and accessible tools for conceiving of and visualizing humanity’s response to the carbon emissions problem (Fig. 1).

Similarly, this paper aims to: 1) to encourage more rigorous consideration of the environmental implications of technological change; 2) to argue that environmental scenarios should incorporation restoration; and 3) to offer new conceptual tools for visualizing humanity’s response to environmental degradation, using climate change as an illustrative example. The new conceptual tools presented may assist in identifying and evaluating policy and ethics implications for the Anthropocene.

1.1. Mitigation is not a complete solution to the carbon and climate problem for the next century

Pacala and Socolow qualified their claim that mitigation efforts “can solve the carbon and climate problem in the first half of this century.” They note that “stabilization at 500 ppm requires that emissions be held near the present level of 7 billion tons of carbon per year” and that “beyond 2054, 500 ppm stabilization is achieved by 50 years of flat emissions, followed by a linear decline of about two-thirds in the following 50 years, and a very slow decline thereafter that matches the declining ocean sink” (2004, p. 968).

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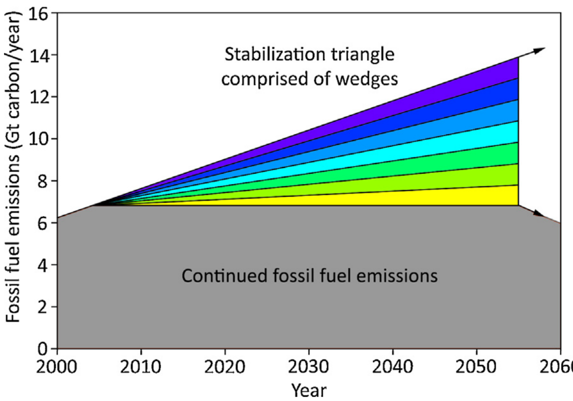

Fig. 1. Stabilization triangle and wedges, adapted from Pacala and Socolow (2004). Each wedge represents an activity that achieves a 1-gigaton reduction in annual fossil fuel emissions of carbon (3.67 $GtCO_2$/year) by mid-century.

While this suggestion is reasonable so long as the "Law of the Hole" applies (i.e. if one is in a hole, stop digging), students in environment courses will reliably observe that merely halting the *growth* of annual carbon emissions does not constitute a complete solution to the carbon and climate problem.

A full solution (if it is possible to a problem as complex as climate change) must chart a three-stage path through: 1) stabilization of emissions; 2) elimination of emissions; and finally 3) carbon dioxide removal (CDR) which restores atmospheric and oceanic carbon to their pre-industrial levels. Stages 1 and 2 comprise mitigation, and are only the first half of a complete solution. Stage 3, comprising restoration, is the second half.

Pacala and Socolow (2004) suggested 15 potential strategies for achieving 1 GtC/year (3.67 $GtCO_2$/year) emissions reductions by mid-century based on existing technology. They assume seven of these strategies can achieve stabilization of emissions at 7 GtC/year (25.69 $GtCO_2$/year) – each constituting one wedge. An updated analysis suggests that this suggestion was over optimistic, and that stabilization might require up to 31 wedges in order to eliminate emissions, and thereby solve only the first half of the carbon and climate problem (Davis et al., 2013).

1.2. CDR and restoration

Pertaining to the second half of the problem, limited research has addressed CDR scenarios necessary for climate restoration (Fuss et al., 2014; Read, 2007; Tavoni and Socolow, 2013; van Vuuren et al., 2013). Researchers are beginning to acknowledge, however, that keeping global warming below 2 °C will involve "a probable reliance on net negative emissions in the longer term" (Peters et al., 2013, p. 4)). The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), for example, noted the role of carbon removals "by sinks in the second half of this century" (UNFCCC, 2015, p. 21, Article 4.1). Bioenergy with carbon dioxide capture and storage (BECCS) also now features prominently in Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2014).

This paper uses the term *restoration* (following the field of restoration ecology) to denote any response to environmental degradation that aims to return part of the Earth system to a prior state of functioning and complexity. Two primary reasons underlie the expanding inquiry in the direction of restoration. First, a fuller examination of possible restoration scenarios shows that present-day planning and policy choices must weigh tradeoffs between: 1) proportional and tipping-point effects that depend on the *magnitude* of impact, versus 2) accumulation effects that depend on the *duration* of impact. Second, charting a course beyond mitigation may help motivate social, political, and entrepreneurial action, given that environmental warnings are difficult for students, policymakers, industry, the scientific community, and the public, when it seems as though the best we can hope for is merely to cease making the problem worse (Schuetze, 2013).

2. The impact pulse

If technological progress continues apace over the course of this century, then an *impact pulse* may idealize the cycle of emissions growth, emissions mitigation, and carbon restoration (Fig. 2). Key turning points punctuate the impact pulse (times $t_{max} - t_{restored}$) and divide the pulse into distinct regions (areas A–F).

Area A represents the ~2.2 trillion tons of cumulative CO_2 emissions to date, with annual emissions in 2015 at nearly 40 billion tons per year (IPCC, 2014).

Area B represents the period of continued acceleration of emissions growth from 2015 to time t_{max}, the maximum growth rate (i.e. where the upward slope of the curve is steepest). Time t_{max} marks an important turning point at which mitigation measures (perhaps resulting from policy changes and modest technological improvements) begin to outweigh the systemic forces that drive emissions growth. (It is possible that we have already reached time t_{max}, although the data are not completely convincing).

Area C represents a deceleration of emissions from time t_{max} to the point of stabilization at time t_{stable} (i.e. where the slope of the curve is zero).

Area D represents a modest decline in the rate of emissions from time t_{stable} to a time when highly effective mitigation measures (i.e. aggressive policy and/or technological remediation) are implemented beginning at time $t_{takeoff}$. Pacala and Socolow (2004) originally idealized the transition from t_{max} to $t_{takeoff}$ (areas C and D) as a period of overall stabilization beginning as soon as possible and lasting until mid-century.

Area E represents the relatively brief period between a time when genuinely effective CDR technology is developed at time $t_{takeoff}$ to a time when zero net emissions (and to a first approximation the point of peak atmospheric CO_2 concentration) are reached at time t_{peak}.

Area F represents the restoration epoch in which humanity deploys CDR technology to repair previous damage. For purposes

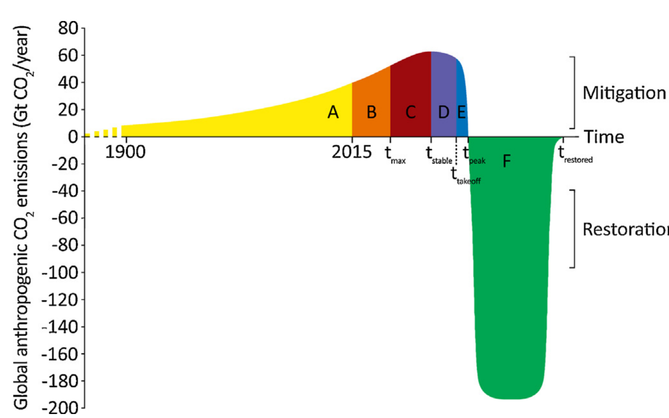

Fig. 2. Impact pulse of carbon emissions. (A) Emissions to date. (B) Continued acceleration of emissions growth. (C) Deceleration of emissions growth. (D) Modest decline in emissions rate. (E) Dramatic decline in emissions rate. (F) Carbon dioxide removal (CDR) reducing atmospheric CO_2 concentration. (A to E) Responses to emissions-related environmental impacts may be characterized as *mitigation*. (F) Responses to emissions-related environmental impacts may be characterized as *restoration*. Times denoting the duration of these stages (t_{max}, t_{stable}, $t_{takeoff}$, t_{peak}, and $t_{restored}$) are dependent upon policy decisions and technical capacity.