RAND JUSTICE, INFRASTRUCTURE, AND ENVIRONMENT

Is Climate Restoration an Appropriate Climate Policy Goal?

Robert J. Lempert, Giacomo Marangoni, Klaus Keller, Jessica Duke

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Preface

Since the 1992 United Nations Framework Convention on Climate Change, society has organized efforts to limit the magnitude of climate change around the concept of stabilization—that is, accepting some climate change but holding it within acceptable bounds. This report offers an initial exploration of the concept of *climate restoration*—that is, approaches that seek to return atmospheric concentrations of greenhouse gases to preindustrial levels within one to two generations. Stimulated by a generous gift to the RAND Pardee Center by Peter and Sharon Fiekowsky, early advocates of climate restoration, this report examines climate restoration through the lens of risk management under conditions of deep uncertainty. This report uses a simple integrated assessment model to explore the technological, economic, and policy conditions under which it might be possible to achieve various climate restoration goals and the conditions under which society might be better off with (rather than without) a climate restoration goal. This report also explores near-term actions that might help manage the risks of climate restoration.

This report should be of interest to those curious about the concept of climate restoration and those interested in expanding the range of options humanity explores in addressing the challenge of climate change.

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The RAND Pardee Center, part of RAND Innovation, aims to enhance the overall future quality and condition of human life by aggressively disseminating and applying new methods for long-term policy analysis (LTPA) in a wide variety of policy areas in which they are needed most. There has been no shortage of past attempts to think globally about the human condition or the long-range future. What has been missing, however, is a means of tying those efforts systematically and analytically to today’s policy decisions. This is the gap the Pardee Center seeks to address.

Questions or comments about this report should be sent to the lead author, Robert J. Lempert (Robert_Lempert@rand.org). Information about the Pardee Center itself and its other projects and initiatives is available online (www.rand.org/pardee). Further inquiries about Pardee Center activities and projects should be sent to the Pardee Center Director, Robert J. Lempert, at Robert_Lempert@rand.org.

RAND Infrastructure Resilience and Environmental Policy Program

The research reported here was conducted in coordination with the RAND Infrastructure Resilience and Environmental Policy program, which performs analyses on urbanization and other stresses. This includes research on infrastructure development; infrastructure financing; energy policy; urban planning and the role of public-private partnerships; transportation policy; climate response, mitigation, and adaptation; environmental sustainability; and water resource management and coastal protection. Program research is supported by government agencies, foundations, and the private sector.

RAND Justice, Infrastructure, and Environment (JIE) conducts research and analysis in civil and criminal justice, infrastructure development and financing, environmental policy, transportation planning and technology, immigration and border protection, public and occupational safety, energy policy, science and innovation policy, space, telecommunications, and trends and implications of artificial intelligence and other computational technologies. For more information about RAND Infrastructure Resilience and Environmental Policy, see www.rand.org/jie/irep or contact the director, Benjamin Preston, at irep@rand.org.

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Proponents envision many types of climate restoration. However, one of great interest—and the focus of this study—seeks to return greenhouse gas (GHG) concentrations to the preindustrial level of 300 parts per million within one to two generations. Climate restoration proponents appear motivated by several factors, including the simplicity and purity of the goal; the potential for a grand challenge to catalyze innovation; and avoiding low-probability, high-consequence risks of extreme climate impacts. On the other hand, climate restoration presents a monumental task, the pursuit of which is not without the potential to do harm by diverting resources away from other responses to climate change or by weakening commitment to other ambitious climate goals.

Therefore, this report considers climate restoration through the lens of risk management. Defined broadly, *risk* is the effect of uncertainty on objectives. Risk management seeks to understand uncertainty's implications and take actions that enhance beneficial opportunities and reduce adverse risks. This broad definition emphasizes that risk management must often be conducted under conditions of deep uncertainty, in which the parties affected by and acting on the risks do not know or agree on the likelihoods of alternative futures or how their actions are related to consequences. Even without a restoration goal, climate change presents an archetypal challenge of risk management under deep uncertainty. Adding climate restoration makes risk management under deep uncertainty even more relevant.

To help judge the appropriateness of a climate restoration goal, we use an augmented version of the Dynamic Integrated Climate-Economy (DICE) model to explore the consequences of pursuing climate restoration over a wide range of plausible futures, with differing assumptions about the cost and performance of technologies that extract carbon from the atmosphere, the cost and performance of GHG mitigation technologies, and the seriousness of unmitigated climate change. Despite numerous simplifications—including a focus on direct air capture (DAC) as representing a much larger suite of proposed approaches—the analysis draws useful conclusions about futures in which climate restoration might prove possible and in which the pursuit of climate restoration might prove catalytic.

If climate restoration proves possible, that is, if society manages to return to preindustrial atmospheric concentrations at reasonable cost, it would reduce the risk of extreme climate impacts and make meeting other climate goals more likely. Successful climate restoration would require achieving future cost and performance of DAC technology equivalent to today's most optimistic assumptions. If the pursuit of climate restoration proves catalytic (i.e., increases the likelihood of widespread deployment of negative emissions technologies), it could open much-needed technology pathways for reducing climate risks—in particular, additional pathways for meeting the 2°C goal. However, even if the pursuit of climate restoration increases the likelihood of DAC deployment, it could also reduce the likelihood of decarbonization so as to counteract any overall beneficial effects. This study suggests that pursuing climate restoration would avoid such moral hazard, that is, provide a net catalytic effect, under conditions in which successful DAC is at least half as likely as successful decarbonization.

The analysis also suggests that near-term actions to help manage any risks from climate restoration might include combining such goals with a 2°C target to reduce the risk of overshoot and developing appropriate long-term financing mechanisms for what might become an expensive public good. In addition, the model dynamics suggest that an ambitious climate restoration goal might seek to achieve preindustrial concentrations toward the end of the 21st century, perhaps around 2075—by some reckonings, the 300th anniversary of the beginning of the Industrial Revolution.

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Abbreviations

BECCS	bioenergy with carbon capture and storage
CO_2	carbon dioxide
DAC	direct air capture
DICE	Dynamic Integrated Climate-Economy
GDP	gross domestic product
GHG	greenhouse gas
GWP	gross world product
IPCC	Intergovernmental Panel on Climate Change
ppm	parts per million
RDM	robust decision making

1. Introduction

Is climate restoration an appropriate goal for humanity's response to climate change? Ambitious goals have long motivated climate policy. The Paris Agreement calls for limiting the increase in global average temperature to below 2°C (global temperatures have already increased about 1°C since the Industrial Revolution). Advocacy groups have called for atmospheric concentrations of greenhouse gases (GHGs) below 350 parts per million (ppm); concentrations are currently at roughly 400 ppm. Ambitious as they are, these goals would all leave the Earth's climate greatly transformed for millennia. Thus, proponents have put forward the even more ambitious goal of *climate restoration*—aiming to return the Earth's climate to its condition before the start of the Industrial Revolution.

Proponents envision many types of climate restoration, but one of great interest—and the focus of this study—seeks to return GHG concentrations to the preindustrial level of 300 ppm within ome to two generations.[1] Because carbon dioxide (CO_2), the most important GHG, remains in the atmosphere for centuries, climate restoration requires extracting GHGs from the atmosphere. However, the need to extract atmospheric CO_2 transcends climate restoration. In recent years, it has become increasingly clear that meeting the Paris Agreement's 2°C target requires a mix of rapid decarbonization and so-called negative emissions. The former involves transforming our energy, transportation, and built environment to slash human greenhouse gas emissions. The latter involves removing GHGs already in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) generates scenarios for meeting the 2°C target. All include sizable amounts of negative emissions, largely from sequestering the emissions from biofuel-powered energy production (called BECCS, for bioenergy with carbon capture and storage). Negative emissions would begin in the coming decades and then, as ("positive") emissions fall, grow to cause a net reduction of atmospheric GHGs after 2050 (Clarke et al., 2014). Climate restoration envisions expanding the suite of negative emissions technologies, in particular direct air capture (DAC), and greatly accelerating the scale and speed of their deployment.

Climate restoration proponents appear motivated by several factors. Envisioning a return to some pristine state often energizes environmental action (Purdy, 2015). As a goal, climate restoration offers a simplicity and purity some find lacking from the Paris Agreement's numeric targets. Grand challenges can also catalyze innovation (Omenn, 2006). Thus, a climate restoration goal may accelerate progress on the innovative technologies for much-needed negative emissions. Taken together, these two factors offer a tantalizing possibility that pursuing

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[1] See, for example, the Healthy Climate Alliance (undated), an organization that promotes climate restoration.

a climate restoration goal may increase society's will, interest, and means to grapple with its climate change challenge. While most economic analysis suggests society should accept some amount of climate change (Nordhaus, 1994; Drouet, Bosetti, and Tavoni, 2015), achieving a restored climate may avoid low-probability, high-consequence risks of extreme climate impacts. Many concerned about climate change are also frustrated by the large gap between current action and what would be required to limit the increase in global average temperature to below 2°C (e.g., Schleussner et al., 2016). Proponents see climate restoration as an attempt to shatter this complacency with an even more compelling and ambitious goal. For some imbued with a sense of environmental stewardship, returning the climate to its preindustrial state seems like the moral thing to do.

On the other hand, climate restoration presents a monumental task, the pursuit of which is not without the potential to do harm by diverting resources away from other responses to climate change or by weakening commitment to other ambitious climate goals. Thus, this report considers climate restoration through the lens of risk management (Renn, 2008). Defined broadly, *risk* is the effect of uncertainty on objectives (Jones et al., 2014). Risk management seeks to understand uncertainty's implications and take actions that enhance beneficial opportunities and reduce adverse risks. This broad definition emphasizes that risk management must often be conducted under conditions of deep uncertainty, in which the parties affected by and acting on the risks do not know or agree on the likelihoods of alternative futures or how their actions are related to consequences (Lempert et al., 2003). Even without a restoration goal, climate change presents an archetypal challenge of risk management under deep uncertainty. Adding climate restoration makes risk management under deep uncertainty even more relevant.

To help judge the appropriateness of a climate restoration goal, we use a simple simulation to explore the consequences of pursuing climate restoration over a wide range of plausible futures, with differing assumptions about the cost and performance of negative emissions technology, the cost and performance of GHG mitigation technologies, and the seriousness of unmitigated climate change. Despite numerous simplifications—including a focus on DAC as representing a much larger suite of negative emissions technologies—the analysis draws useful conclusions about futures in which climate restoration might prove possible and in which the pursuit of climate restoration might prove catalytic.

If climate restoration proves possible, that is, if society manages to return to preindustrial atmospheric concentrations at reasonable cost, it would reduce the risk of extreme climate impacts and make meeting other climate goals more likely. Successful climate restoration would require achieving future cost and performance of DAC technology equivalent to today's most optimistic assumptions. If the pursuit of climate restoration proves catalytic (i.e., increases the likelihood of widespread deployment of negative emissions technologies), it could open much-needed technology pathways for reducing climate risks, in particular opening up additional pathways for meeting the 2°C goal. Even if the pursuit of climate restoration increases the likelihood of DAC deployment, it could also reduce the likelihood of decarbonization

(Campbell-Arvai et al., 2017) so as to counteract any beneficial effects of negative emissions. This study suggests that pursuing climate restoration would avoid such moral hazard, that is, provide a net catalytic effect, under conditions in which successful DAC is at least half as likely as successful decarbonization.

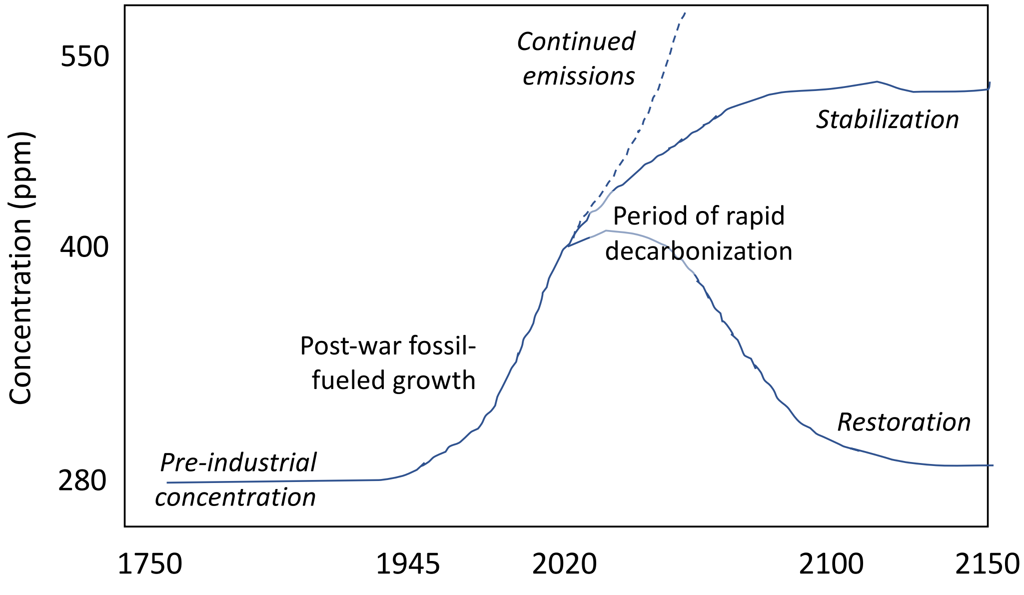
The analysis also suggests that near-term actions to help manage any risks from climate restoration might include combining such goals with a 2°C target to reduce the risk of overshoot and developing appropriate long-term financing mechanisms for what might become an expensive public good. In addition, the model dynamics suggest that an ambitious climate restoration goal might seek to achieve preindustrial concentrations toward the end of the 21st century, perhaps around 2075—by some reckonings, the 300th anniversary of the beginning of the Industrial Revolution.

2. Climate Restoration and Risk

For many millennia, average human living standards changed little. The average family at the start of the 18th century had about the same material wealth and used about the same amount of energy as the average family in antiquity (Maddison, 2001). The Industrial Revolution shattered this stasis. Fueled in large part by the consumption of fossil fuels, first coal and then oil, economies grew and living standards rose. This rapid rise began in Europe and the United States, but then, particularly after World War II, expanded globally. In the past 70 years, the world's economy has grown more than tenfold. In the past two decades alone, 1 billion people have risen out of extreme poverty (*Economist*, 2013).

Concurrently, this activity has significantly altered the composition of the Earth's atmosphere. As shown in Figure 2.1, concentrations of heat-trapping GHGs are now 40 percent higher than the 1780s level of approximately 280 ppm, with three quarters of the rise occurring since the 1970s. GHGs remain in the atmosphere for decades to centuries and have already begun to considerably change the Earth's climate. These long residence times, combined with the thermal inertia of the Earth's climate system means that the climate would continue to change for many decades, even if all emissions ceased today.

Figure 2.1. Atmospheric Greenhouse Gas Concentrations With and Without Climate Restoration



In response, the world's nations, on paper at least, have committed to stabilizing concentrations of atmospheric GHGs at a level chosen to avoid dangerous climate change (United Nations Framework Convention on Climate Change, 1992). Choosing a safe stabilization level requires a mix of ethical and scientific judgments, complicated by both an inequitable mix of consequences—the poor and those living in particularly vulnerable areas, such as low-lying island states, will likely suffer more severely from climate change than the rich and those living in other locations—along with the deep uncertainty that surrounds the scientific understanding of the consequences of any particular level of GHGs (e.g., Moss, 1995; Keller et al., 2005; Drouet, Bosetti, and Tavoni, 2015).

The world community has settled on a goal of holding the increase of global average temperature to no more than 2°C above the preindustrial values.[1] This goal implies stabilizing at a currently uncertain concentration ranging from barely above preindustrial levels to sizably beyond. The concentration level consistent with the 2°C goal depends in part on the value of the climate sensitivity, a key scientific uncertainty reflecting the response of the Earth's climate to increased concentrations of GHGs (e.g., Rogelj et al., 2014; Olson et al., 2012; D. Harvey, 2007; Weitzman, 2012).

Whatever temperature limit society deems safe, achieving it typically requires rapid decarbonization—that is, over a small number of decades converting a global economy that currently relies on fossil fuel combustion for more than 80 percent of its energy to one that will meet the needs of roughly 9 billion people with little or no net emissions of GHGs (Harvey et al., 2013). Doing so will require a significant increase in energy efficiency in the global energy, transportation, building, industrial, and agricultural sectors, as well as elimination of the conventional combustion of fossil fuels, replaced by some combination of other sources, such as renewable energy, nuclear power, or carbon capture and storage. This transformation would presumably occur alongside the tens of trillions of dollars in investment that the world needs to make in energy, transportation, and other infrastructure systems in the coming decades to meet development goals (IPCC, 2014). Decarbonization might increase these costs by several percent and would certainly involve the flow of trillions of dollars from different economic sectors and different regions of the world (Keller et al. 2005; Clarke et al., 2014; IPCC, 2014).

Climate restoration envisions adding another ambitious layer to this decarbonization effort—deploying a vast range of human-made equipment and enhancing biophysical processes to extract the additional CO_2 already in the atmosphere. Most recent scenarios from the IPCC (Clarke et al., 2014) and other organizations (White House, 2016) that envision meeting the 2°C goal do so by including negative emissions from such sources as land management and cultivating biofuels (plants grow by extracting carbon from the atmosphere), burning those fuels to generate energy, then capturing and sequestering the CO_2 effluents underground. As suggested

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[1] The text of the Paris Agreement can be found online (United Nations, 2015).

in Figure 2.1, climate restoration would advance the timing and greatly expand the scale and scope of such activity.

Climate Restoration Technology

Various means exist to extract CO_2 from the atmosphere. The most straightforward approaches include reforestation (i.e., growing trees) along with improved management of agricultural and natural lands. While beneficial, reforestation and improved land management alone cannot achieve the required carbon removal from the atmosphere (Psarras et al., 2017). Technologies that might be deployed at the appropriate scale include DAC, BECCS, and enhanced biophysical systems, such as iron fertilization of the oceans, enhanced weathering, and ocean alkalinization (Buesseler et al., 2008). This report focuses on DAC, because it appears to have the least potential for troubling externalities, such as disruption of ecosystems and competition for agricultural lands.

Many new firms currently work on DAC technologies.[2] Most envision someday deploying thousands to millions of machines through which ambient air would pass. Mass-producing these machines would allow economies of scale that would slash costs. Chemical reactions within the machine would extract the CO_2. One DAC approach employs an anionic exchange resin that absorbs CO_2 when dry and releases it when wet (Lackner, 2013). The approach dries the resin, exposes it to ambient air, moves the resin to a chamber where it is exposed to moisture, captures the released CO_2, and then repeats the process indefinitely. Another approach employs wet capture solutions to achieve similar results. For example, Carbon Engineering has developed a process for reacting CO_2 with a calcium- and hydroxide-based solution to form calcium carbonate pellets, which are decomposed to release purified CO_2 for storage. The firm estimates capturing 1 million tons of CO_2 per year at commercial scale, at costs of $100 to $150 per ton of CO_2 captured, purified, and compressed (Keith et al., 2015).

Captured carbon can be sequestered in appropriate underground geological formations, such as those that have sequestered oil and gas for millions of years. Even more intriguingly, some proponents envision sequestering captured carbon by using it to create the construction materials, such as concrete and aggregate, for building 21st-century cities and other infrastructure needed for a world population that could reach 9 billion or more middle-class people by century's end. The potential market for such products made of captured carbon is deeply uncertain. However, as one suggestion of the possibilities, the firm Blue Planet's process passes air through a solution that dissolves the CO_2 and then combines it with calcium cations (Ca^{2+}) to form calcium carbonate (Constantz and Bewernitz, 2014). The calcium carbonate coats seed particles to form an aggregate, which can then be combined with cement to form concrete. Blue Planet's current

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[2] See the Air Miners website for a list of such firms (Air Miners, undated).

prototype is selling aggregate from captured carbon—reportedly at a profit[3]—to San Francisco International Airport for terminal renovations, using calcium extracted from waste concrete.[4]

DAC has different thermodynamic requirements than processes that extract carbon from the effluent of fossil fuel–powered plants. The CO_2 concentration in such effluent is about 30,000 ppm (Zevenhoven and Kilpinen, 2001), and the scrubbers aim to extract nearly 100 percent of the GHGs spilling from the plant. DAC operates on air with much lower GHG concentrations, in some ways a more difficult challenge. However, a useful DAC process need only extract roughly half of the CO_2 in the air that passes through it, which allows operations at high efficiency. Lackner (2013) calculates that a process such as his could reduce CO_2 from 400 ppm to 200 ppm at a theoretical thermodynamic efficiency of 90 percent. The resulting energy requirements are low, with a theoretical lower bound of roughly 20 kJ/mol of CO_2, about 5 percent of the energy released from the combustion that produced the mole of CO_2. In addition, DAC often requires only low-grade (and thus often low-cost) waste heat, such as that used for drying Lackner's resins.

While future DAC might reach high thermodynamic efficiency, any significant contribution to climate restoration would require operations on an enormous scale. To extract 1 Gt CO_2 from the atmosphere, machines that reduced CO_2 concentrations from 400 ppm to 200 ppm would need to process 5,000 Gt of air, an amount that would cover roughly the area of the Earth's landmass with a layer 20 m thick. Not surprisingly, cost estimates range widely. Advocates envision that low-cost energy and other inputs, combined with learning by doing and mass production that drives down the manufacture and operations costs, could direct capture for as low as roughly \$50/tCO_2 extracted. Therefore, such machines would process the 5,000 Gt of air for about \$50 billion. Our society currently produces millions of cars each year—fantastically complicated, much abused, but highly reliable machines—for a cost per pound roughly equal to that of a steak. The radiators on these cars also process in one year on the order of 5,000 Gt of air. Whether DAC can reach such levels of cost and performance is currently deeply uncertain.

Considering Trade-Offs

People often bring different world views to potentially transformative and contentious topics, such as climate restoration. World views consist of coherent clusters of policy preferences, expectations about the future, mental models of how the world works, and valued objectives. To understand the relevant risks and opportunities, it can prove useful to tease apart these world views and ask what happens if we pursue a policy suitable for one view of the future but a different future comes to pass.

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[3] Personal communication with Brent Constantz, Blue Planet's chief executive officer.

[4] Other possible calcium sources include brine from desalination plants and wastewater facilities, which produce water with excess cations. Naturally occurring seawater and geological brines can also provide a calcium source.

Table 2.1 shows such an exercise, using what some have called a "utopia-dystopia" matrix (van Asselt and Rotmans, 1997). The columns show two near-term policy choices—pursuing climate restoration or not pursuing such a goal. The rows show relevant futures, chosen so that each policy has at least one future with which it is consistent (colored green) and with which it is inconsistent (colored light red). The former represents ideal outcomes deserving, at least in some cases, of the label "utopia." The latter represents unfavorable outcomes that may rise to the level of dystopic. Table 2.1's rows show three futures, which we label "climate restoration is possible"; "climate restoration is not possible but potentially catalytic"; and "climate restoration is neither possible nor catalytic." This study's modeling exercise in Chapter 3 provides more precise definitions. For now, we note that these futures highlight two ways in which pursuing a climate restoration goal might lead to desirable outcomes. Such a pursuit could actually restore the climate, that is, return it to atmospheric concentrations of 300 ppm. Alternatively, pursuit of the goal could fail to reach 300 ppm but could nonetheless help catalyze widespread diffusion of negative emissions technologies, as well as help catalyze increased public commitment to addressing climate change.

As noted in Table 2.1's first row, actually reducing atmospheric concentrations to 300 ppm over the course of the 21st century could have important benefits. First, in many cases (but not all, as discussed below) meeting other climate goals, such as 2°C, is a lesser included case of climate restoration—that is, reaching 300 ppm in many cases holds global mean temperature increases to below 2°C by century's end. In addition, climate restoration could reduce the risks of extreme climate impacts beyond those set forth in the Paris Agreement goals. The climate is a complex system being pushed past familiar bounds. Many Earth system processes operate at time scales of decades or longer—for example, the warming of the oceans, melting of ice sheets, and changes in ecosystems (Applegate et al., 2015; Hansen et al., 1984). Science has only an imperfect understanding of the effects of heightened GHG concentrations. Thus, there is no guarantee that the system is not close to, or even beyond, catastrophic thresholds, such as an irreversible melting of the Greenland and Antarctic ice sheets, which could result in many meters of sea level rise (Alley et al., 2005; Kriegler et al., 2009). In addition, a GHG level that seems safe for a few years may not remain safe for decades. If successful, restoration would offer insurance against (presumably) low-probability, high-consequence climate effects.

As noted in Table 2.1's second row, even if it proves impossible to reach 300 ppm, pursuing a climate restoration goal might catalyze increased public commitment to addressing climate change, as well as increase effort toward deploying negative emissions technologies. Such technologies are required at some level to meet the 2°C goal even with relatively optimistic assumptions regarding decarbonization. The more widely available negative emissions technologies become, the more they provide a hedge against the failure of one or more decarbonization pathways and thus make achieving 2 °C even more likely.

Table 2.1. Utopia-Dystopia Matrix Suggesting Consequences of Pursuing Climate Restoration Goal in Futures Consistent (Green) and Inconsistent (Light Red) with That Goal

	Near-Term Actions	
Future World	**Pursue Climate Restoration**	**Do Not Pursue Climate Restoration**
Climate restoration is possible	• Reduce risks of changed climate • Meet other climate goals *Additional risks to manage:* o *Temperature overshoot* o *Overreliance on negative emissions* o *Temporal mismatch between funding needs and available revenues* o *Slowing negative emissions once at large scale*	• Increase risks of changed climate • Decrease likelihood of meeting other climate goals (moral hazard)
Climate restoration is not possible but potentially catalytic	Increase likelihood of meeting 2°C goal due to more • Public commitment to addressing climate change • Interest in negative emissions technologies *Additional risks to manage:* o *Inability to fail gracefully*	Decrease likelihood of meeting other climate goals (moral hazard)
Climate restoration is neither possible nor catalytic	• Waste resources on costly and ineffective efforts • Decrease likelihood of meeting other climate goals	• Avoid costly, ineffective effort • Avoid diverting resources from more effective activities

This study is not the place for a detailed analysis of the extent to which the additional opportunities implied by a climate restoration, as opposed to a 2 °C, goal would incentivize entrepreneurs and financiers to pursue negative emissions. Nor is this study the place to evaluate how climate restoration, as an alternative framing of the climate challenge, might enhance public commitment. It is possible, however, to offer some hypotheses.

Climate restoration proponents emphasize that while other climate goals aim to limit humanity's damage, climate restoration aims to return the Earth's climate to its condition before the start of the fossil fuel–powered Industrial Revolution. Proponents also emphasize the excitement of new technology. Relevant to the latter, psychologists find that many people only acknowledge a problem as serious when offered acceptable solutions.[5] Climate restoration—in

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[5] From the behavioral decision sciences, the majority of the evidence suggests that coupling risk information with a specific plan not only elevates perceived risk but also motivates behavior change (Fischhoff and Davis, 2014). This finding is particularly clear in the public health field (Leventhal, 1965; Witte and Allen, 2000) and also found in the climate risk communication literature (Pidgeon and Fischhoff, 2011).

particular to the extent that captured carbon is recycled into building materials rather than sequestered underground—introduces a seemingly elegant and inoffensive technological solution to what otherwise might appear an intractable challenge.

Relevant to the former, climate restoration seems to emphasize a sense of purity with its goal of returning the atmosphere to an earlier, less sullied state. More broadly, the environmental thinker Jedediah Purdy (2015) defines four schools that characterize several centuries of American environmental thought: the *Providential*, in which nature serves human needs if people apply their labor and ingenuity; the *Romantic*, which focuses on the aesthetic and spiritual value of pristine nature; the *Utilitarian*, which views nature as a storehouse of resources requiring scientific management; and the *Ecological*, which views nature as a complex, interconnected system likely to respond in unexpected ways to human intervention. Proponents could argue that climate restoration addresses all of them. It resonates with the Providential and Utilitarian views, avoids trespass on the Ecological, and offers to salvage the Romantic.

On the other hand, Table 2.1's third row notes that if climate restoration is neither possible nor catalytic, pursuing it could waste resources and decrease the likelihood of meeting other climate goals. Society has many needs, and the funds available to address climate change are necessarily limited. Focusing on climate restoration might reduce near-term investment in other technologies that in the end prove more consequential. Undue confidence in our ability to remove CO_2 from the atmosphere and store it safely might reduce public commitment to incur the near-term costs of not emitting GHGs in the first place. Embracing a climate restoration goal that eventually proves infeasible might reduce the legitimacy of other ambitious climate policy goals.

Pursuing climate restoration in futures in which it is possible or catalytic also could create additional risks that need to be managed, as noted in the first two rows of Table 2.1. These risks, and the overall trade-offs posed by climate restoration, are the subject of the rest of this report.

A Simulation Model and Beyond

To help illuminate these trade-offs, to quantify the futures in Table 2.1, and to suggest near-term actions that might balance among risks and rewards, we adopt a simple, simulation model–based evaluation of climate restoration under conditions of deep climate, technological, and economic uncertainty. We employ the simulation in a multiscenario decision analytic process called robust decision making (RDM), a leading approach for risk management under deep uncertainty (Lempert et al., 2003; Lempert et al., 2006). The study explored the consequences of pursuing a climate restoration goal over a wide range of plausible futures, including those in which DAC technology do and do not achieve the technological capabilities to make it an attractive option and in which the technology exists alongside decarbonization options that are either expensive or inexpensive. These explorations help quantify the trade-offs sketched in Table 2.1.

Because simulation models are necessarily narrow abstractions of reality (in particular, the one used here), this study also considers how factors not included in the simulations might most significantly affect its conclusions. Most salient, the modeling considers DAC as the only source of negative emissions, so the study's discussion sought to generalize from this narrow focus. Similarly, this study's multiscenario modeling explores a wide range of futures but neglects learning within each simulation run. Therefore, the study only qualitatively explored pathways in which evolving circumstances cause climate policy goals to be adjusted over time, either because the goal proves too difficult to meet or because pursuing the goal in the near term catalyzes technology breakthroughs that open up new possibilities for the future.

Overall, the simulation multiscenario modeling and the commentary it supports offer initial answers to three sets of questions:

1. What combinations of assumptions regarding technology cost, performance, and other factors are consistent with a future in which climate restoration might be considered possible?
2. What might it mean for a climate restoration goal to be catalytic?
3. How can the risks of climate restoration be managed in those futures in which it does seem possible or catalytic?

3. Computational Experiments

Like many RDM exercises, this study employs an "XLRM" framework (Lempert et al., 2003) to help guide the model development and data gathering. The XLRM framework, shown in Table 3.1, is useful because it helps organize relevant factors into the components of a decision-centric analysis. The letters X, L, R, and M refer to four categories of factors important to RDM analysis: metrics (M) that quantify the objectives that decisionmakers seek to achieve; policy levers (L) that decisionmakers use to pursue these objectives; uncertainties (X) that might affect the connection between policy choices and outcomes; and relationships (R), often instantiated in simulation models, of outcomes to uncertainties and levers.

In this study, we regard the near-term decision to pursue a particular climate restoration goal as the policy lever. The analysis then explores the potential positive and negative consequences of making such a choice. In particular, we consider as **policy levers (L)** the choice to pursue one of four climate goals:

- 2°C: Hold the increase in global mean temperature to less than 2°C by 2100.
- Restore 2050: Reduce atmospheric concentrations of GHGs to 280 ppm by 2050.
- Restore 2100: Reduce atmospheric concentrations of GHGs to 280 ppm by 2100.
- Restore 2100 and 2°C: Both reduce atmospheric concentrations of GHGs to 280 ppm and hold the increase in global mean temperature to less than 2°C by 2100.

We assume the near-term decision to pursue a climate goal has two effects. First, it launches society along a planned pathway that combines decarbonization and carbon capture to achieve that goal. Second, it catalyzes the near-term research, investment, and policies needed to enable travel along that pathway. The analysis addresses the first effect by calculating optimal pathways of emissions abatement and carbon capture and sequestration consistent with each goal and reporting as outcomes the resulting costs, financial flows, and temperature/concentration pathways. To address the second effect, the study considered cases in which the act of pursuing a goal in the near term may affect the future cost and performance of decarbonization and DAC technologies.

To provide a first-cut evaluation of the implications of these goals, we use a modified version of the 2016 Dynamic Integrated Climate-Economy (DICE) model as our **relationships (R)** (Nordhaus, 2017-a). DICE is a highly aggregated and commonly used integrated assessment simulation that couples a Ramsey economic growth model with a simplified representation of the climate system (National Academies of Science, Engineering, and Medicine, 2016). DICE calculates long-term GHG mitigation paths optimal from a traditional single-objective, utilitarian social welfare perspective (Adler et al., 2017). The study considered the policy levers as constraints on optimization.

Table 3.1. Key Factors in the Analysis

Uncertainties (X)	Policy Levers (L)
DICE model parameters: • Climate sensitivity [2°C, 3.1°C, 4.5°C] • GHG abatement costs [225, 450, 650 $/tCO$_2$] • Carbon capture o Costs [50, 200, 500 $/tCO$_2$] o Diffusion speed [5, 10, 15%/year] • Half-life of sequestered carbon [150, 5,000 years] • Market for carbon products o Marginal cost [0, –50 $/tCO$_2$] o Market size [1, 10 GtC/year] Parameters for post-processing model results: • Effect of restore goals on o Abatement costs o Carbon capture costs	Goals: • 2°C • Restore 2050 • Restore 2100 • Restore 2100 and 2°C

Relationships (R)	Metrics (M)
• DICE model o Modified to include carbon removal and two types of sequestration o Used abatement and carbon capture trajectories that optimize present value social welfare	• Net present value social welfare • Annual cost of abatement and carbon capture • Damages due to climate change • Maximum global temperature and atmospheric concentration • Maximum annual cost of meeting climate goal

The temperature goal is defined as an upper threshold holding from 2100 onward, consistent with most climate policy frameworks, such as the Paris Agreement, which are tacit on the tolerated magnitude and duration of any threshold exceedance (Geden and Löschel, 2017). The restoration goals are similarly defined as upper thresholds holding from the specified date (2050 or 2100) onward.

Previous work by Keller, McInerney, and Bradford (2008) included DAC in DICE. In addition to employing the model in an RDM analysis, we augment the Keller, McInerney, and Bradford (2008) representation with two sequestration options, one underground and the other in building materials (e.g., aggregate and cement). The appendix provides a full list of model equations.

Our DICE model represents DAC technology as directly reducing atmospheric concentrations of GHGs and assumes DAC increases energy demand (3.64 EJ/GtCO$_2$ removed from the atmosphere), has a constant unit cost per ton of CO$_2$ captured, and has a maximum annual deployment growth rate. For simplicity, we omitted in this study the cost reductions from learning by doing originally included in Keller, McInerney, and Bradford (2008). Therefore, the assumed DAC costs represent the asymptotic values after learning has occurred. This simplification overestimates the amount of carbon captured in the near term but has little effect on the cumulative accounting. For instance, when running the version of the model with learning by doing, more than 90 percent of the carbon is captured after the costs have dropped significantly from their initial toward their asymptotic values.

In the model, the carbon captured by DAC can be sequestered underground. The model represents this process with a constant unit cost embedded in the capture costs and a leakage rate, proportional to cumulative storage, that adds to atmospheric GHG concentrations. Carbon captured by DAC can also be sequestered in construction materials, a process represented with a constant marginal cost, which can be negative to reflect potential revenues from selling such materials, and a maximum annual market size for any such sales (assumed constant over time).

DICE calculates deployment time series for abatement and carbon capture over a time horizon starting in 2015 and ending in 2260, with a five-year step. Each calculated pathway meets the specified climate policy goal and maximizes net present value of social welfare using a single-objective utilitarian function. As additional **metrics (M)**, the model reports annual deployment rates and costs for these technologies, along with the global temperature, GHG concentrations, and damages due to climate change. The model also reports the maximum cost, temperature, and GHG concentration in any given year. The study used these metrics to compare the desirability of alternative pathways and the potential consequences of pursuing alternative climate goals.

One run of the DICE model provides optimal abatement, carbon capture, and sequestration time series, constrained by the choice of climate goal, for each of many plausible future states of the world. These time series are contingent on the assumed future, represented by a set of values for each of seven **uncertainties (X)**, as shown in Table 3.1. In each future, the model calculates an optimal pathway assuming perfect information. Each decarbonization pathway is represented by an emissions control rate time series, with 0 percent control in any time period corresponding to full reliance on fossil fuels and 100 percent to a fully carbon-free energy system using the most cost-effective mix of renewables, nuclear power, and other decarbonization options. This study made no attempt to calculate how near-term pathways might hedge against uncertainty or trace out adaptive pathways that respond to new information (Keller et al., 2004). Rather, the study generated insight by comparing optimal pathways in different futures.

The uncertain input parameters each affect the model results in different ways. Uncertainty in the value of the climate sensitivity model input parameter affects the difficulty in reaching the 2°C goal, with higher parameter values resulting in greater warming for the same increase in cumulative emissions. The model represents the cost of GHG abatement as a power function in the emissions control rate, with an exponent of 2.6, representing increasing difficulty in providing reliable and cheap energy as the carbon-free fraction grows. Uncertainty in these costs is represented by a coefficient for the upper bound of the power function and affects the optimal amount of abatement in meeting climate goals. This upper bound cost declines over time with exogenous technological progress. Uncertainty in the cost and performance of DAC is represented by the constant cost of extracting a ton of CO_2 from the atmosphere and the maximum rate (diffusion speed) at which the annual amount of extracted carbon can grow. Uncertainty in the markets for the carbon produced by DAC is represented by a negative cost (e.g., revenues) per ton of carbon extracted and an annual cap on the amount of carbon that can be sold in revenue-generating products. These uncertain parameters all affect the optimal amount of carbon capture in meeting climate goals. The model assumes that any carbon not sold in products is sequestered underground. We do not explicitly consider the sequestration requirements for any carbon captured from power plant effluent. Therefore, we leave for future work consideration of any potential conflicts between the storage requirements of DAC and carbon capture from fossil plants.

The climate sensitivity and GHG abatement cost values shown in Table 3.1 spans a reasonable subset of reported estimates (e.g., Olson et al., 2012; Drouet, Bosetti, and Tavoni, 2015; Knutti, Rugenstein, and Hegerl, 2017). The range of carbon capture costs and diffusion speeds reflects the values provided by recent assessments (National Research Council, 2015) and those offered in interviews with entrepreneurs and advocates.[7] The carbon product profit and market size range from values representing no such markets to those envisioned by entrepreneurs and advocates.

Except where noted otherwise, we consider the full range of uncertainties for all four goals, in particular, considering the same range of assumptions for the cost and performance of DAC technology for both the 2°C and Restore goals.

In postprocessing the model results, we also use two additional uncertain parameters, as noted in Table 3.1, that represent in a highly abstract way the possibility that pursuing a climate restoration goal in the near term increases the likelihood of future low-cost carbon capture technology and reduces the likelihood of future low-cost abatement technology. This part of the analysis is described in the box at the end of Chapter 4.

This modified DICE model is implemented as a nonlinear program in Pyomo, an open-source software package for mathematical modeling in Python, and solved with IPOPT, a software package implementing an interior point algorithm for large-scale nonlinear optimization. The DICE model calculates the optimal abatement and carbon capture trajectories in each future, assuming perfect information. We employ a full-factorial design over the seven uncertainties and run the DICE optimization in each of $3^4 \times 2^3 = 648$ future states of the world[8] for each of the four policy levers considered. This generates a large database of runs. Each entry in the database represents one climate policy goal in one future and the resulting outcomes. Chapter 4 uses visualizations and statistical analysis to summarize the information in this database. The model code and the model input and output data are available on request from one of the authors.

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[7] We thank Brent Constantz, Peter Eisenberger, David Keith, and Klaus Lackner for very helpful interviews.

[8] Four uncertain parameters, each with three possible values, and three uncertain parameters, each with two possible values.

4. Simulation Results

We use this multiscenario RDM framework to explore, both quantitatively and qualitatively, the conditions consistent with a future in which climate restoration might be considered possible, what it might mean for a climate restoration goal to be catalytic, and how can the risks of climate restoration can be managed in those futures in which it does seem possible or catalytic.

Conditions Under Which Climate Restoration Is Possible

The multiscenario analysis suggests that there are more pathways to the Restore 2100 than the Restore 2050 goal and fewer pathways to Restore 2100 than to 2°C.

Figure 4.1 shows the most cost-effective atmospheric global concentrations pathways for reaching the Restore 2050 and Restore 2100 goals in each of the many future states of the world.[9] The Restore 2100 goal yields a wide range of pathways. Some rise to concentrations over 600 ppm around 2075 before dropping rapidly to 280 ppm by 2100. Others never rise much above 435 ppm before dropping to 280 ppm, some before the century's end (as early as 2060 or 2075). In contrast, Restore 2050 is only achievable in a narrow range of pathways, all peaking below 435 ppm and then dropping rapidly to meet the mid-century goal.

As one measure of socioeconomic feasibility, we assume that society's willingness to pay to reach these climate goals is limited. In particular, we assume that society will only accept pathways for which the annual cost of meeting the climate goal—GHG mitigation and carbon capture and sequestration, less any revenue from carbon-based products—is never greater than 2 percent of gross world product (GWP) per year, roughly the fraction of the gross domestic product (GDP) that the world currently devotes to military spending (World Bank, undated). This value clearly represents only one judgment regarding the resources people would be willing to devote to address climate change. During World War II, for instance, the United States devoted roughly 40 percent of its GDP to the pursuit of victory (Chantrill, undated). Figure 4.1 uses green to denote the pathways that meet this 2 percent GWP criterion and red to denote those that do not. The green pathways correspond to Table 2.1's future in which climate restoration is possible.

This 2 percent GWP constraint considerably limits the fraction of feasible pathways. Table 4.1 shows the fraction of low-cost pathways that meet each of the four goals. About 11 percent of the pathways for Restore 2100 reach the goal without exceeding this 2 percent GWP threshold in any year, as compared to 2 percent for the 2°C goal. The simulation also

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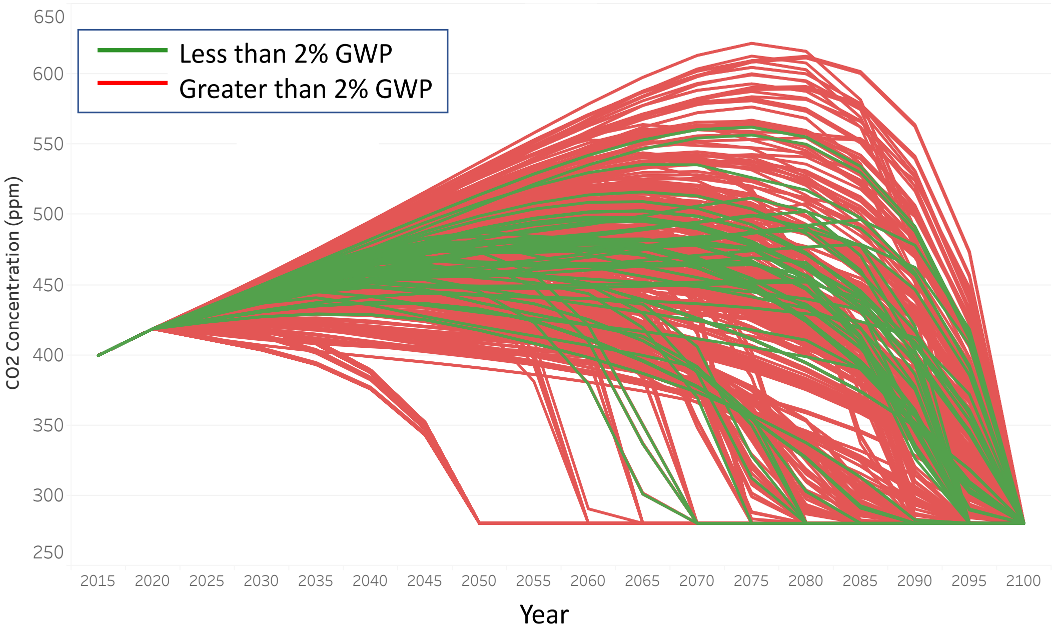
[9] The model cannot solve (i.e., reach the desired goal) in every future. Figure 4.1 only shows those futures that the model can solve, specifically 2,105 out of 2,592 (roughly 78 percent).

shows no pathways for Restore 2050 consistent with this cost constraint. Note that these pathway counts do not represent probabilities, which would depend on the likelihood ascribed to the various combinations of uncertainties.

Figure 4.1. Concentration Pathways for Restore 2050 and Restore 2100 Goals



NOTE: Green and red colors show the pathways with costs less or more than 2 percent of GWP.

Table 4.1. Fraction of Low-Cost Pathways

Goal	Fraction of Total Pathways
2°C (with DAC)	21.9%
2°C (without DAC)	11.1%
Restore 2050	0.0%
Restore 2100	11.4%
Restore 2100 and 2°C	11.6%

Rather, these counts suggest the conditions under which the goals are missed or met within the cost constraints.[10] Combining the 2°C and Restore 2100 goals slightly increases the number

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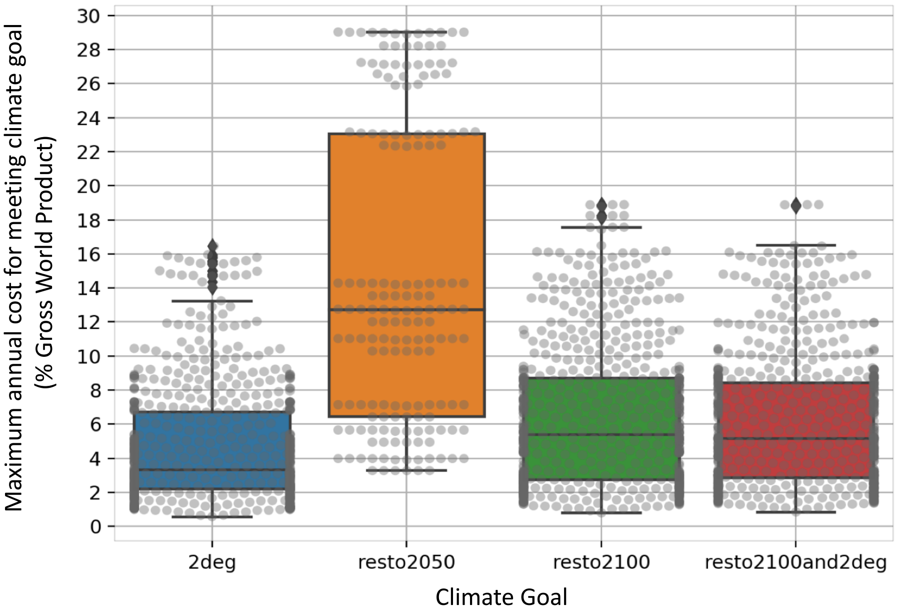
[10] As in Figure 4.5, RDM analysis often uses imprecise probabilities to distinguish between alternative policy options toward the end of the analysis, rather than as inputs at the beginning.

of low-cost pathways relative to Restore 2100 alone, because the combined two goals flatten the cost incurred over time in some futures whose pathways would otherwise exceed the 2 percent GWP cost threshold late in the century by letting GHG concentrations rise to high levels before rapidly (and expensively) dropping to the target level.[11]

These patterns in Figure 4.1 are relatively insensitive to the precise value of the 2 percent GWP cost constraint. Figure 4.2 shows the distribution of maximum annual cost for meeting all four goals. The Restore 2050 goal shows no pathways with a maximum annual cost of less than 3.3 percent of GWP. In contrast, the distributions for the 2°C, Restore 2100, and Restore 2100 and 2°C goals are all roughly similar and have many pathways that satisfy the cost constraint. Under some conditions, all four goals can generate very high annual costs, exceeding 15 percent or more of GWP. Overall, Figure 4.2 suggests that many more pathways to climate restoration would be available if society were willing to devote 10 percent to 20 percent of GWP to the endeavor.

Under what conditions is it possible to meet the goals within the 2 percent GWP cost constraint? Figure 4.3 answers this question with the results of a statistical "scenario discovery" analysis, which identifies the combinations of uncertainties most important to enabling low-cost pathways to the various climate goals (Lempert, 2013).

Figure 4.2. Maximum Annual Cost of Meeting Each Climate Goal in Each of 648 Futures



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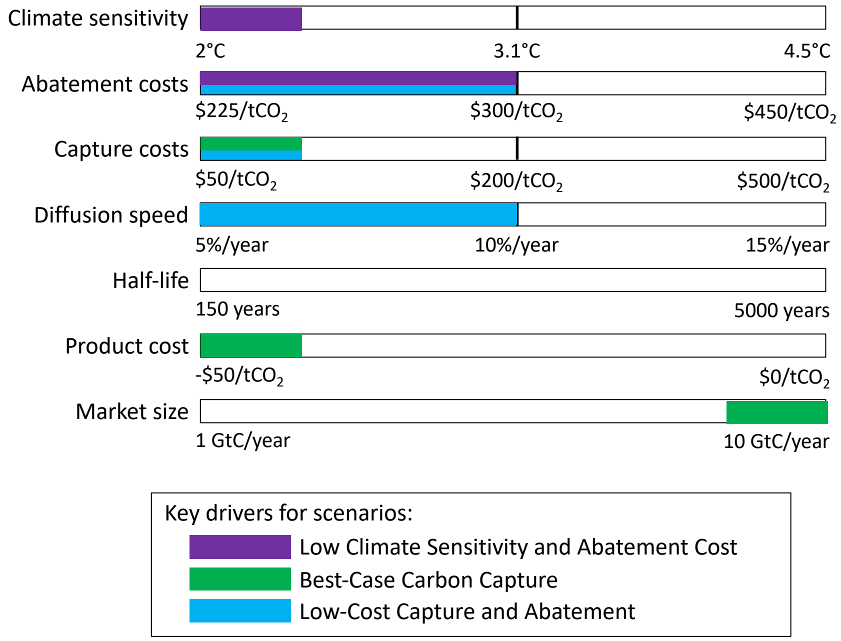
[11] This study does not give the DICE model the 2 percent GWP threshold as a constraint. Doing so would limit the information we could glean from a large set of runs, since the model would not be able to reach the climate goals in most futures.

Figure 4.3. Conditions Under Which the 2°C, Restore 2100, and Restore 2100 and 2°C Goals Can Be Met with Annual Cost Never Exceeding 2 Percent of GWP



Three scenarios emerge from this analysis, summarizing all the possible ways to reach the 2°C and Restore goals. Low-cost pathways generally fall within one of the following scenarios:

1. **Low Climate Sensitivity and Abatement Cost** scenario, defined as having a climate sensitivity of 2°C and abatement cost less than or equal to $\$300/tCO_2$
2. **Best-Case Carbon Capture** scenario, with capture costs of $\$50/tCO_2$, a market size of 10 GtC/yr for captured carbon that sells for roughly $\$50/tCO_2$
3. **Low-Cost Capture and Abatement** scenario, with capture costs of $\$50/tCO_2$, abatement cost less than or equal to $\$300/tCO_2$, and a diffusion speed of DAC technology of 10 percent per year or less.

As shown in Table 4.2, low-cost pathways to the 2°C goal generally fall in the Low Climate Sensitivity and Abatement Cost scenario or in the Best-Cast Carbon Capture scenario. Low-cost pathways to the Restore 2100 or Restore 2100 and 2°C goals generally fall in the Best-Case Carbon Capture scenario or Low-Cost Capture and Abatement scenario. If a pathway does not meet the criteria defining one of these scenarios, it will generally have high costs. Overall, this analysis suggests that Table 2.1's "climate restoration is possible" future corresponds to the **Best-Case Carbon Capture** or **Low-Cost Capture and Abatement** scenario as defined in Table 4.2. These scenarios also inform the discussion of benefits and costs below.

Table 4.2. Scenarios Required to Meet Climate Goals and the Density/Coverage Measures of Their Comprehensiveness

Goal	Scenario 1	Scenario 2	Set of Scenarios
2°C	**Low Climate Sensitivity and Abatement Cost** scenario D/C = 96%/49%	**Best-Case Carbon Capture** scenario D/C = 51%/35%	D/C = 83%/70% Cases common to both: • 2% of total cases • 8% of low-cost cases
Restore 2100	**Best-Case Carbon Capture** scenario D/C = 69%/50%	**Low-Cost Capture and Abatement** scenario D/C = 83%/41%	D/C = 91%/74% Cases common to both: • 2% of total cases • 16% of low-cost cases
Restore 2100 and 2°C	**Best-Case Carbon Capture** scenario	**Low-Cost Capture and Abatement** scenario	D/C = 88%/73% Cases common to both: • 2% of total cases • 16% of low-cost cases

NOTE: D/C = density/coverage.

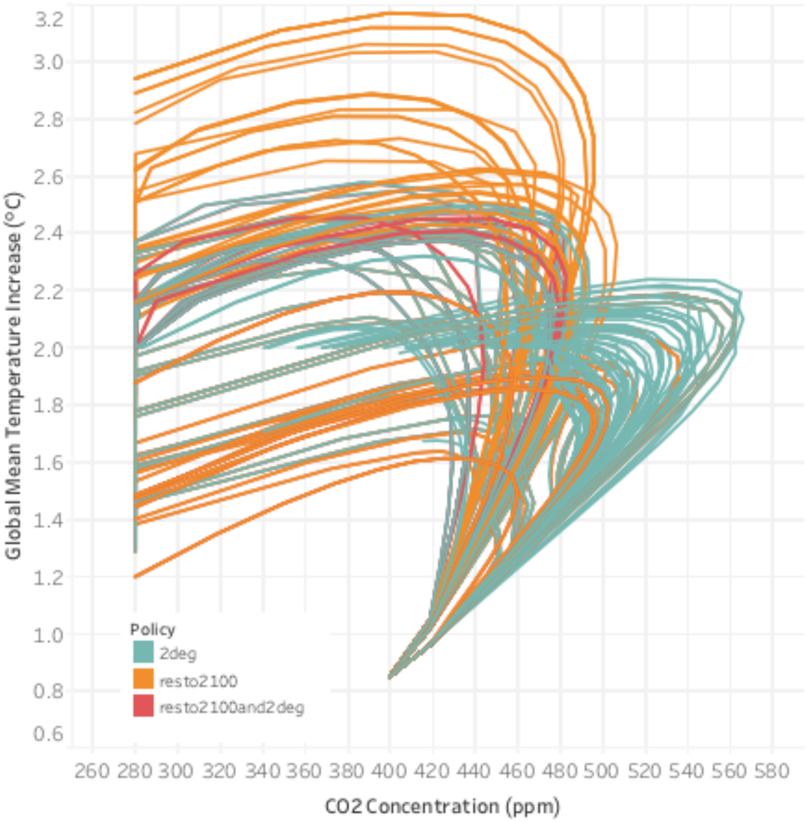
Table 4.2 also provides quantitative measures of the statement that a low-cost pathway “generally falls in” a scenario. The table shows density and coverage metrics for each scenario (Bryant and Lempert, 2010). Density is the fraction of pathways meeting the criteria for each scenario that is, in fact, low cost. Coverage is a fraction of all the low-cost pathways that meet each scenario criteria. It is also worth noting that the scenario discovery analysis identifies factors that are less important in meeting the various goals. In particular, the half-life of carbon sequestered underground plays a lesser role in distinguishing low-cost from higher-cost pathways to climate restoration.

Managing Additional Risks

Even in scenarios in which it appears possible, pursuing climate restoration creates the potential for adverse consequences—in particular, a danger of overshoot and decreased incentives for decarbonization. The analysis helps identify such risks and suggests ways to reduce them.

Overshoots occur when a pathway allows global temperature or concentration to rise past desirable bounds expecting that DAC will bring it safely back down. Risk arises if that expectation may turn out to be wrong. For instance, some Restore 2100 pathways allow temperatures to rise above 3°C, as shown in Figure 4.4. Such pathways occur in futures with low climate sensitivity. Because this study does not consider uncertainty in the climate impacts as a function of temperature change, climate sensitivity is also a proxy for the social welfare implications of changed global temperatures. Low climate sensitivity implies smaller effects from high temperatures. Similarly, some 2°C pathways allow concentrations to rise very high in futures with low climate sensitivity and low-cost DAC. In such futures, the model can reduce the net present value of addressing climate change by waiting to extract large amounts of carbon from the atmosphere late in the century.

Figure 4.4. Concentration and Temperature Pathways for Various Goals



Both sets of pathways are vulnerable to broken assumptions. For example, if the world starts down a Restore 2100 pathway that initially allows higher concentrations, then subsequently discovers climate sensitivity is higher than expected, it may prove difficult to avoid sizable climate damages. If the world starts down a high-concentration 2°C pathway and subsequently discovers climate sensitivity or DAC costs are higher than expected, significant climate damages may also prove difficult to avoid. This potential for overshoot emphasizes the need to embed climate restoration in a risk-management approach to climate change. In particular, Figure 4.4 suggests that pursuing the combined Restore 2100–and–2°C goal reduces these potential overshoots with little effect on the fraction of low-cost pathways, shown in Table 4.1.

Conditions Under Which Climate Restoration Is Catalytic

Proponents see climate restoration as catalytic, helping to increase the likelihood of widespread DAC deployment and public commitment to address climate change. On the other hand, the concern that pursuing negative emissions technologies might decrease the incentives to decarbonize the global economy represents one of the most persistent criticisms of reliance on such technologies (Anderson and Peters, 2016). Often termed *moral hazard*, this concern reflects the tendency for people to act irresponsibly or recklessly if they believe they are protected from the consequences of their actions. For example, building levees to reduce the risk from relatively small floods can encourage more people to move into high-risk flood plains.

To explore what it might mean for climate restoration to prove catalytic and, conversely, its potential for moral hazard, we first note that the simulation suggests significant benefits if DAC deployment does become more likely. In particular, comparing model runs with and without DAC technology makes clear that DAC opens additional pathways for achieving the current 2°C goal and reducing the risk of extreme climate damages.

Running the DICE model without DAC, our analysis shows only a narrow window for meeting the 2°C goal. As shown in Table 4.1, twice as many of the considered pathways meet the 2°C goal when the model is allowed to use DAC than when it is not. With DAC, both the Low Climate Sensitivity and Abatement Cost or Best-Case Carbon Capture scenarios offer low-cost pathways to the 2°C goal. Without DAC, only pathways in the former scenario are available.

In addition, the availability of DAC creates options for reducing the most serious risks of climate change. Note that in Figure 4.1 about 13.5 percent of the low-cost Restore 2100 pathways reach 280 ppm before century's end. The scenario discovery analysis in Figure 4.3 identifies low DAC cost and climate sensitivity as the uncertainties most important to determining whether or not the Restore 2100 goal is met early. When DAC costs are low ($50/t$CO_2$) and climate sensitivity is relatively large (4.5°C), the potential for high damages from climate change makes it most cost-effective to meet the goal before century's end. That is, carbon capture capabilities that might be catalyzed by the Restore 2100 goal provide additional pathways to reduce concentrations more quickly in those futures in which a high climate sensitivity threatens dangerous climate change.

To place these results in the context of potential moral hazard, we note that the combination of two factors—the costs of decarbonizing the global economy and the impacts of unmitigated climate change—yield four very different views of the climate change challenge. As noted by Morton (2015) and by Wagner and Weitzman (2015), many advocates focus on two less-challenging combinations: one in which climate change could cause serious damage, but the costs of reducing emissions are small; and the other in which reducing emissions is expensive, but climate change causes little damage. We can call the former the **Easy to Be Green** scenario.[12] In addition, there exist two other combinations: one in which both damages and decarbonization costs prove low and one with both high decarbonization costs and significant climate damage. This latter combination, which we might call the **Big Problem** scenario, is the one in which an increased likelihood of DAC might prove most important. However, pursuing climate restoration might make the **Easy to Be Green** scenario less likely.

We can use our database of simulation model results to explore this trade-off between making the **Big Problem** scenario potentially easier to address but making **Easy to Be Green** scenario potentially less likely. Assume that setting a near-term climate restoration goal increases the likelihood of low-cost negative emissions because it focuses research, investment, and policy toward advancing the requisite technology and policies. Assume that concurrently setting such a goal reduces the likelihood of low-cost decarbonization because it shifts research, investment, policy commitment, and consumer behavior away from technologies and policies that reduce GHG emissions. Moral hazard is a concern if the net result of pursuing a climate restoration goal makes desirable scenarios less likely rather than improving outcomes in any one scenario.

Figure 4.5 shows this trade-off (see the box at the end of the chapter for the calculations that generated this figure). If confident that decarbonization will prove costly, decisionmakers might decide that the improved expected outcomes of **Big Problem** more than outweigh any decrease in the likelihood of achieving the **Easy to Be Green** scenario, even if the likelihood of low-cost DAC is low. However, if the **Easy to Be Green** scenario is already likely, decisionmakers may demand that low-cost DAC prove likely before committing to a climate restoration goal. Both the **Big Problem** and **Easy to Be Green** scenarios are characterized by the potential for large climate effects. The trade-offs between moral hazard and catalytic climate restoration are similar in cases with small climate effects, but they are more demanding for the likelihood of low-cost DAC, as also shown in Figure 4.5.[13]

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[12] Note that the Low Climate Sensitivity and Abatement Cost scenario discussed above is a special case of the Easy to Be Green scenario.

[13] As with the colors on Figure 4.1, the specific numbers here clearly depend on the rather arbitrary definition of 2 percent GWP as low cost, but the general patterns are insensitive to this value.

Figure 4.5. Conditions Under Which Pursuing the Restore 2100 Goal Does and Does Not Create a Moral Hazard

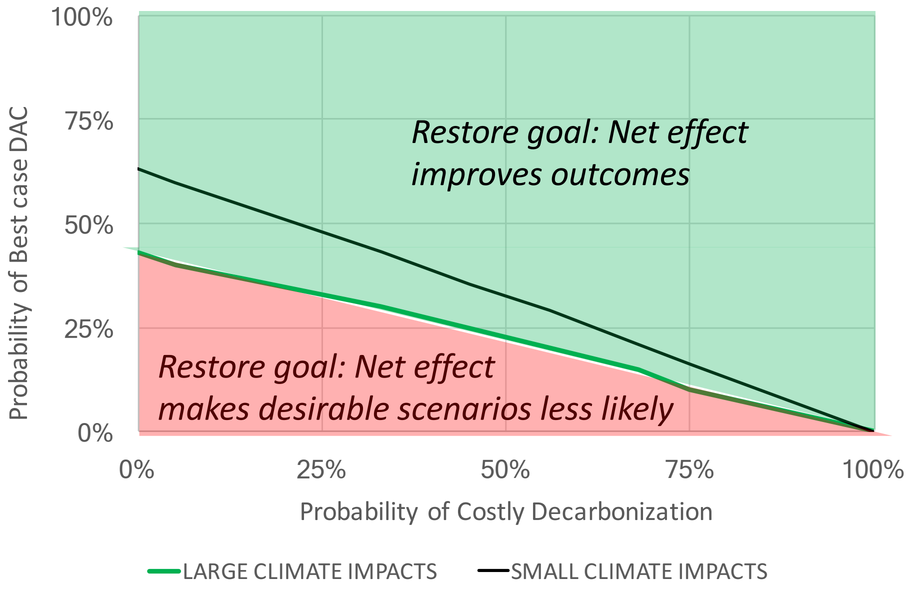


Table 4.3. Parameter Values for the Representative Futures for Each of the Scenarios Used in Figure 4.5

	Low Value	High Value
Climate sensitivity	2°C	4.5°C
GHG abatement costs	\$225/tCO_2	\$650/tCO_2

Table 4.4. Parameter Values for the Representative Futures with the Best- and Worst-Case DAC Scenarios

	Best-Case DAC	Worse-Case DAC
Capture costs	\$50/tCO_2	\$500/tCO_2
Diffusion speed	15%/year	5%/year
Half-life	5000 years	150 years
Product cost	–\$50/tCO_2	\$0/tCO_2
Market size	10 GtC	1 GtC

Policy Persistence

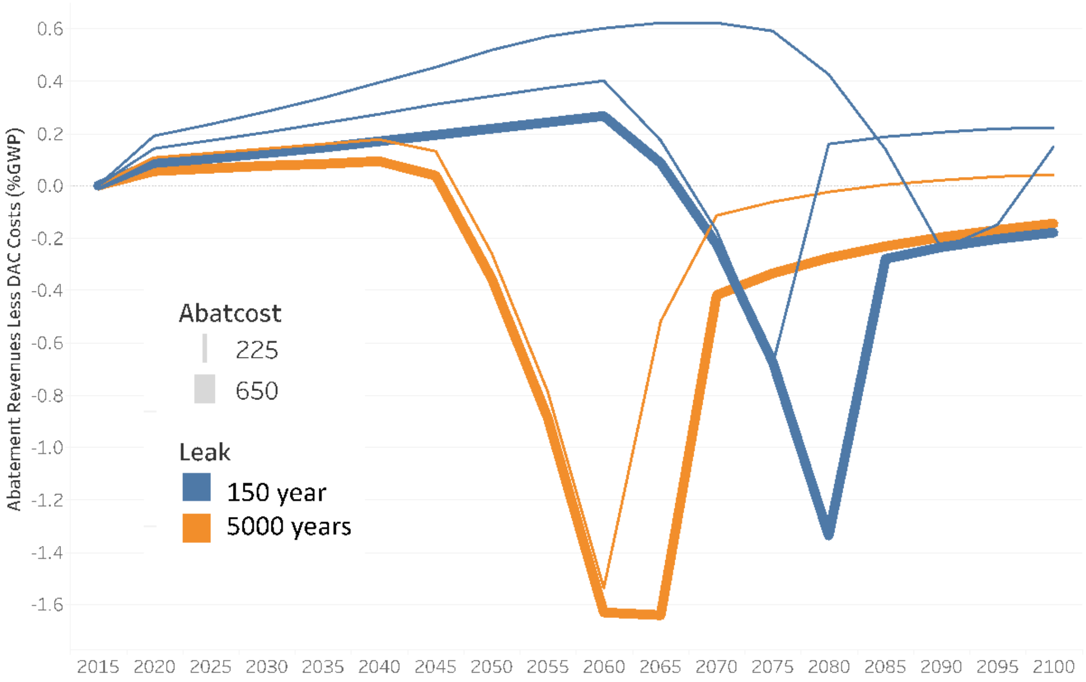
To successfully manage the risks from climate change, today's climate policies should encourage actions that continue for decades. History suggests, however, that some policy reforms lead to societal changes that persist over the long-term, while others fade away without long-term effects. Those reforms that do persist often create constituencies that benefit and support the reform over time (Patashnik 2003, 2008). Climate policies that create such constituencies may significantly increase the decarbonization rate over the 21st century (Lempert, 2007; Isley et al., 2015).

Climate restoration appears to have some features that may encourage, and others that may detract from, such policy persistence. Pursuing a climate restoration goal could create an industry with many billions of dollars in annual revenues devoted to removing carbon from the atmosphere and potentially selling carbon-based construction materials to developers worldwide. This industry and its customers would represent a constituency that might be expected to encourage the persistence of policies, investments, and research needed to reach a climate restoration goal. This could prove beneficial from a societal point of view, while growing negative emissions were needed to stabilize the climate. Once atmospheric concentrations had begun to fall, however, the large negative emissions industry might unduly influence society's judgment of the appropriate level at which to stabilize those concentrations.

In addition, maintaining the appropriate flow of revenues to this industry over time might present challenges. Climate restoration represents a public good, one that benefits every person, not just those who pay for it. Assume that society funds climate restoration with the revenues from a carbon price on GHG emissions. Such a "polluter pays" principle, in which those responsible for environmental damages pay for repairing them, often generates more political support than devoting other societal resources to such purposes.

Figure 4.6 thus shows the net flow of revenues from GHG mitigation to climate restoration for five pathways to the Restore 2100 goal, with different assumptions regarding abatement costs (\$225 and \$650/GtCO$_2$) and the half-life of carbon sequestered underground (150 years and 5,000 years). We choose these cases because they achieve climate restoration at low cost. When abatement is costly (thick lines), the most cost-effective pathways have intensive (a few decadeslong) bursts of DAC, resulting in a large net flow of funds—far beyond those available from any carbon price—to climate restoration. A short half-life of sequestered carbon (150 years) delays and reduces this burst of direct capture in the most cost-effective pathways. This need for a large infusion of nonclimate-related funds may undercut any long-term commitment to a climate restoration goal. Spreading DAC over longer periods of time would reduce this concentrated need for funds, but it would also increase the overall cost of the pathway.

Figure 4.6. Flow of Funds Between Decarbonization and Carbon Capture in Selected Futures



Exploring Moral Hazard

A simple policy experiment helps to explore the conditions under which pursuing climate restoration presents or avoids a moral hazard.

We begin by choosing a representative future for (1) each of the four combinations of assumptions regarding decarbonization cost and climate impacts discussed in the text and (2) best- and worst-case DAC scenarios. Tables 4.3 and 4.4 show the parameters for these representative scenarios. The model calculates a net present value for meeting the 2°C goal in each of these eight scenarios, denoted by $NPV_{C,D}^{s}$, where $C = Costly, Inexp$ for costly and inexpensive decarbonization, $D = Best, Worst$ for best- and worst-case DAC, and $s = Large, small$ for large and small climate damages. Assume prior probabilities P_{Costly} and P_{Best} represent, respectively, the likelihood of costly decarbonization (Table 4.3) and best-case DAC (Table 4.4). As a function of these two priors, the expected net present value of pursuing the 2°C goal for large and small climate damages is thus given by

$$\begin{aligned}\overline{NPV}^{s}\left(P_{Costly}, P_{Best}\right) &= P_{Costly}P_{Best}NPV_{Costly,Best}^{s} + P_{Costly}\left(1 - P_{Best}\right)NPV_{Costly,Worst}^{s} \\ &\quad + \left(1 - P_{Costly}\right)P_{Best}NPV_{Inexp,Best}^{s} + \left(1 - P_{Costly}\right)\left(1 - P_{Best}\right)NPV_{Inexp,Worst}^{s}\end{aligned}$$

How might pursuing climate restoration affect this expected value? As noted in the report, we assume such a goal increases the probability of the best-case DAC but decreases by an equal percentage the probability of low-cost decarbonization, with new probabilities given by

$$\begin{aligned}P'_{Best} &= Min[(1 + \varepsilon)P_{Best}, 1] \\ P'_{Costly} &= P_{Costly} + \varepsilon\left(1 - P_{Costly}\right)\end{aligned}$$

where ε represents the positive and negative effect of setting the goal on the two probabilities. Pursuing climate restoration thus changes the expected value

$$\Delta\overline{NPV}^{s}(P_{Costly}, P_{Best}) = \overline{NPV}^{s}(P'_{Costly}, P'_{Best}) - \overline{NPV}^{s}(P_{Costly}, P_{Best})$$

Note that this difference only considers the effect of pursuing a climate restoration goal on expectations, not on the pathway actually traveled.

Pursuing climate restoration thus avoids a moral hazard when the net expected benefit is greater than zero, that is, $\Delta\overline{NPV}^{S}(P_{Costly}, P_{Best}) > 0$. Figure 4.5 shows the sets of prior probabilities for which this condition is satisfied and thus the expectations that might lead decisionmakers to favor pursuing climate restoration.

5. Conclusions and Recommendations

Over the past 250 years, the scale of human activity has grown roughly fifty-fold. At the start of the Industrial Revolution, humanity consisted of roughly 1 billion people with average annual per capita incomes of $100 and average annual per capita energy consumption equivalent to 100 barrels of oil, primarily from burning wood. Today, humanity consists of more than 7 billion people, with average annual incomes of $6,000 and average annual energy consumption equivalent to 5,000 barrels of oil, primarily from burning oil and other GHG-emitting fossil fuels. The resulting vast increase in human well-being has also unleashed climate change, which ensues from the accumulation of heat-trapping GHGs in the atmosphere. Perniciously, the bulk of these gases remain in the atmosphere for centuries—therefore, even if all emissions ceased today (an impossibility), the climate would continue to change. It would take a millennium for the climate to return to its preindustrial conditions.

Meeting the Paris Agreement 2°C goal represents a vast challenge, requiring ubiquitous, worldwide technological and behavioral changes at an unprecedented rate. It is by no means certain that society can accomplish the task. Climate restoration also clearly represents a vast and uncertain enterprise. The question is whether adding this even more ambitious goal enhances or detracts from humanity's efforts to address the climate change challenge.

Interest in climate restoration is motivated by its potential for risk reduction, moral clarity and increased opportunities for "bottom-up" innovation, as well as its potential to motivate public commitment to climate action. Most simply, proponents suggest that the pursuit of climate restoration could catalyze the deployment of technologies that make it easier—and, in fact, may prove necessary—to achieve less ambitious goals, such as the 2°C target. In addition, successful climate restoration could reduce risks by significantly shortening the time that humanity coexists with high levels of atmospheric GHG concentrations. The Earth system has numerous and poorly understood processes that operate on decadal and longer time scales, along with many nonlinear thresholds beyond which deleterious effects suddenly become significant and sometimes irreversible (Alley et al., 2002; Keller et al., 2005; Wuebbles et al., 2017). Living with elevated GHG concentrations may resemble sitting on a loaded spring that can release at any time. Returning concentrations to preindustrial levels could reduce such risk.

Climate restoration also offers a certain moral clarity. The 2°C goal, as with any such stabilization target, embodies often-unacknowledged trade-offs among the perceived costs of decarbonization and benefits of doing so (see, for example, Garner, Reed, and Keller, 2016). Despite claims that it rests solely on science, any such stabilization target easily unpacks into an array of potentially contestable moral judgments. Proclaiming a climate restoration goal also clearly involves moral judgments and trade-offs, but it offers a purity and clarity missing from any stabilization target.

For its advocates, climate restoration also offers a useful frame for enhancing the public's commitment to addressing climate change. In part, the moral clarity helps. In addition, while climate restoration offers no magical silver bullet (because it can only succeed when accompanied by deep decarbonization), the goal does suggest an elegant technological contribution to what can otherwise seem like a hopeless challenge. Pursuing climate restoration may also energize new, bottom-up efforts to address the challenge, attracting entrepreneurs and advocates who (in the near term, at least) can pursue the goal independent of any need for near-universal societal commitment to the endeavor. In the longer term, the pursuit of climate restoration has some favorable policy persistence characteristics. If the technology proves viable, a growing climate restoration industry might promote policies favorable to its continuation and growth.

However, successful climate restoration would require, not surprisingly, that the technological capabilities unfold very favorably. Our analysis suggests that to achieve climate restoration, entrepreneurs' most optimistic assumptions about DAC technology must come to pass. Therefore, the likelihood of achieving climate restoration is by no means guaranteed. The question becomes one of whether it is better to proclaim a compelling but exceedingly ambitious goal, or refrain because it is not at all certain the goal can be achieved.

This study provides one framework to help adjudicate this question, by considering a scenario in which pursuing climate restoration increases the likelihood of successful DAC while decreasing by a similar amount the likelihood of low-cost decarbonization. Applied across a range of the futures considered in the analysis, this very narrow framing concludes that pursuing a climate restoration goal generates net benefit if the prior likelihood of DAC (that is, prior to committing to the goal) is not less than about half of the prior likelihood of low-cost decarbonization. Thus, those who believe low-cost decarbonization is highly likely will be less persuaded by the benefits of the carbon restoration goal than those who would fear that low-cost decarbonization is not assured. Additional considerations, not addressed in this study, are also important. These include opportunity costs and the dangers of overshoot. They also include judgments about the extent to which the moral clarity and potential to motivate action change the basic premise of the moral hazard scenario. If the overall effect of climate restoration is to increase commitment to climate action, then it generates a net benefit independent of its prior likelihood of success.

This study's simple simulation clearly omits numerous important factors. Its exclusive focus on DAC—only one potential source of negative emissions—overemphasizes the demands climate restoration would place on that technology. In reality, BECCS, ocean fertilization, and other approaches would likely share the burden of extracting carbon from the atmosphere. But among these technologies, DAC appears to have the least adverse side effects. Therefore, to the extent that this study overemphasizes the required scale of DAC deployment, it also may underestimate some of the adverse consequences of pursuing climate restoration with a broader technology portfolio. This study's simulations also only compare pathways along which climate restoration is pursued with perfect information. The simulations do not explore adaptive pathways that evolve in response to new information, thus making it more difficult to assess the actual opportunities and risks inherent in pursuing a novel and potentially transformative technology as part of a complex process of social learning in the face of deep uncertainty.

Nonetheless, this study does suggest near-term steps that might help manage the risks of a climate restoration goal, that is to increase the likelihood of beneficial outcomes while reducing the likelihood of adverse impacts.

First, the study suggests that advocates might aim to restore the climate, not by 2050, but later this century. The earliest low-cost restoration pathways in the simulation reach preindustrial concentrations roughly six decades from now, by some accounts the tercentenary of Watt's steam engine and, thus, the Industrial Revolution. Perhaps Restore 2075 would provide a better balance than 2050 between a not-implausible and sufficiently resonant goal.

Second, to avoid the risk of overshoot, a climate restoration goal might best be combined with a temperature target, such as 2°C. The simulation suggests that the combined goal is no less difficult than a separate restore goal and reduces the risk of pathways that rely on rapid deployment of carbon capture systems late in the 21st century.

Third, successfully returning atmospheric GHG concentrations to preindustrial levels would likely require near-term attention to longer-term financing mechanisms. In the near term, entrepreneurs can innovate and demonstrate DAC technology using existing sources of financing. In the longer term, climate restoration represents an expensive public good. Experience suggests that society often underfunds its public goods. Therefore, it is entirely plausible that whatever the merits, the funds would not be made available when it comes time to make large investments in the climate restoration endeavor. As one solution, society might pay for climate restoration with the revenues from any carbon price used to incentivize decarbonization. Such a linkage between the principle of "polluter pays" and the cost of cleanup often resonates with the public. However, this simulation suggests that climate restoration has large funding demands temporally distant from the flow of carbon price revenues, thus suggesting a need for some type of cross-generational funding mechanisms.

In addition, the simulation suggests that any linkage between carbon price revenues and expenditures on carbon capture should be phased in slowly. The simulation shows many pathways that pursue what turn out to be a poorly balanced mix of decarbonization and climate restoration, resulting in either overshoot or high annual costs. Given the current deep uncertainties regarding the future cost and performance of these technologies, it might be best to delay the time when they are both linked directly to the same carbon price.

Finally, this analysis suggests that the most important near-term step for shifting balance toward opportunities and away from adverse effects might be for society to embrace a risk management framework and to regard its response to climate change as a process of policy experimentation. Based in a philosophy of evolutionary learning, such policy experimentation acknowledges the uncertainty and ambiguity inherent in complex societal problems, the partial perspectives we bring to them, the necessary incompleteness of any current understanding, and the importance of a well-structured and empirically grounded process of testing, rejecting, and improving potential solutions to societal challenges (Ansell, 2011; Stilgoe, 2015). Pursuing climate restoration opens up new potential pathways to solve climate change, heretofore unexplored scenarios. However, none of these scenarios are guaranteed. Climate restoration thus calls for a learning process. The best we can do is pursue climate restoration with a passion while embedding it in a process of testing, experimentation, correction, and discovery.

Appendix: Modifications to the DICE Model

The model used in this study is based on the 2016 version of DICE (Dynamic Integrated Climate-Economy model of the economics of global warming), which has been used to provide one of the most recent estimates of the social cost of carbon (Nordhaus, 2017-a). References to its basic set of equations can be found in the corresponding published article (Nordhaus, 2017-b), with further information available in the user manual accompanying a previous version (Nordhaus and Sztorc, 2013). Below, we highlight the parameters, variables, and equations that have been added or changed specifically for this study, in order to accommodate and account for direct air carbon capture and sequestration.

As we focus on the 21st century, we consider a time horizon of 50 out of the original 100 time steps, five years each, from 2015 to 2260. Yearly anthropogenic emissions over time *step t-1* (*E*[*t-1*], $GtCO_2/yr$) cumulate into the atmosphere, increasing the concentration of CO_2 at time *t* (*MAT*[*t*], *GtC*). In our code, part of these emissions can be offset by a chosen yearly amount of carbon captured from the air (*ESEQDAC*[*t-1*], $GtCO_2/yr$):

$$MAT[t] == MAT[t-1]*b11 + MU[t-1]*b21 + (E[t-1]-ESEQDAC[t-1])*tstep*12/44.$$

b11, *b21* and *MU* are climate parameters and variables as part of the original DICE carbon cycle modeling; *tstep* is the number of years in a time step; and *12/44* converts $GtCO_2$ into *GtC*.

DAC requires energy to operate, which we assume to be equal to 3.64 EJ per unit of $GtCO_2$ sequestered (*seqdac_cons*). In current DAC technologies, roughly 15 percent of this energy consumption is electric and the rest is thermal, mostly natural gas. Given average carbon intensities of power production ($\sim 0.13\ GtCO_2/EJ$) and natural gas combustion ($\sim 0.055\ GtCO_2/EJ$), we obtain an estimate of $0.067\ GtCO_2$ baseline CO_2 emission penalty for operating DAC for one EJ (*seqdacpen2co2*). The resulting additional DAC emissions (*ESEQDACPEN*[*t*], $GtCO_2$) are then

$$ESEQDACPEN[t] == seqdacpen2co2 * seqdac\_cons * ESEQDAC[t].$$

Industrial carbon emissions (*EIND*[*t*], $GtCO_2/yr$) increase accordingly, unless mitigated through additional replacement of fossil fuels in the global energy system with carbon-free alternatives (*MIU*[*t*], abated fraction of gross industrial plus DAC-related emissions):

$$EIND[t] == (1 - (MIU[t])) * (sigma[t] * YGROSS[t] + ESEQDACPEN[t]).$$

sigma[*t*] represents projected baseline industrial $GtCO_2$ emissions per unit of GDP (*YGROSS*[*t*], *T$*), gross of any climate damages.

To model inertia in DAC deployment and avoid unrealistic behaviors, we limit the rate of diffusion from one time step to the next (*seqdac_maxgrowth*, *%/yr*), starting from year 2025:

$$\mathit{ESEQDAC}[t] <= (1+\mathit{seqdac\_maxgrowth}/100)**\mathit{tstep} * \mathit{ESEQDAC}[t-1].$$

An absolute upper bound of *1 GtC* holds in year 2020, which is assumed to be the initial year for DAC to be able to operate at large scale.

Part of the captured CO_2 is reused for construction materials (*ESTOR_MARKET*[*t*], $GtCO_2$). The remainder is stored underground (*ESTOR_GROUND*[*t*], $GtCO_2$):

$$\mathit{ESEQDAC}[t] == \mathit{ESTOR\_MARKET}[t] + \mathit{ESTOR\_GROUND}[t].$$

The carbon sequestered and stored underground cumulates in a potentially leaky reservoir (*MRES*[*t*], *GtC*):

$$\mathit{MRES}[t] == \mathit{tstep} * 12/44 * \mathit{ESEQDAC}[t] + \mathit{resret} * \mathit{MRES}[t-1],$$

where resret is the reservoir retention rate per 5 years, equal to $0.5\hat{}(1/\mathit{reshalflife}/\mathit{tstep})$, given the half-life time of the reservoir (*reshalflife*, *yr*). The resulting flux of leaking carbon emissions (*ECCSLEAK*[*t*], $GtCO_2/yr$) becomes

$$\mathit{ECCSLEAK}[t] == 44/12 * (1-\mathit{resret}) * \mathit{MRES}[t-1].$$

Leaking emissions are combined with endogenous industrial emissions (including DAC) and exogenous land-use emissions (*etree*[*t*], $GtCO_2/yr$) to provide overall CO_2 anthropogenic emissions:

$$E[t] == \mathit{EIND}[t] + \mathit{etree}[t] + \mathit{ECCSLEAK}[t].$$

Each ton of CO_2 sequestered from the air has a unit cost of *mcostseqdac0* dollars, inclusive of additional transport and processing costs, so that the overall DAC expenditures (*SEQDACCOST*[*t*], *T$/yr*) amount to

$$\mathit{SEQDACCOST}[t] == 1e\text{-}3 * \mathit{mcostseqdac0} * \mathit{ESEQDAC}[t].$$

Part of this cost can be offset by negative costs because of potential revenues from the market of construction products incorporating sequestered carbon, expressed in the model as negative costs (*MKTSTORCOST*[*t*], *T$/yr*), resulting from a certain unitary negative cost (*mcoststor_market0*, $\$/tCO_2$):

$$MKTSTORCOST[t] == 1e{-}3 * mcoststor\_market0 * ESTOR\_MARKET[t].$$

The market is capped at *maxestor_market GtC*/*y*r to represent a realistic finite demand for such products. All costs are then accounted for, changing the original DICE budget equation:

$$Y[t] == YNET[t] - ABATECOST[t] - SEQDACCOST[t] - MKTSTORCOST[t],$$

where we subtract from the GDP net of climate damages (*YNET*[*t*], *T$/yr*) all the costs related to climate change mitigation: abatement (*ABATECOST*[*t*], *T$/yr*), operation of DAC, and correction for revenues of DAC-derived market products. We then obtain the wealth available for investments in final goods (*Y*[*t*], *T$/yr*).

The rest of the model follows the standard DICE 2016 model structure and parameterization. Given the multitude of scenarios considered, we gain computational efficiency by fixing the fraction of GWP allocated to savings at business-as-usual levels.

Table A.1 maps the uncertainties listed in Table 2.1 with DICE parameter names, which are either explained in the previous paragraphs or part of the original model equations.

Table A.1. Map of Uncertainties Listed in Table 2.1 with DICE Parameter Names

Uncertainty	DICE Parameter
Climate sensitivity	t2xco2
GHG abatement costs	Pback
Carbon capture, costs	mcostseqdac0
Carbon capture, diffusion speed	seqdac_maxgrowth
Half-life of sequestered carbon	Reshalflife
Market for carbon products, marginal cost	mcoststor_market0
Market for carbon products, market size	maxestor_market

t2xco2 represents the equilibrium temperature impact of a doubling in CO2 concentration, while *pback* is the cost of abating an additional tonCO2 under a hypothetical full abatement scenario happening today. In general, this represents the maximum unitary cost of abatement, as this declines over time and when decreasing abatement.

Policy levers are implemented as upper or lower bounds of DICE variables, enforced during the optimization. Metrics are computed a posteriori from optimized variable levels. The code is available on request from the authors.

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