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Sherry Rowland Tribute

Addressing the Anthropocene

A. D. Anbar,[A,B,E] *S. J. Romaniello,*[A] *B. R. Allenby*[C] *and W. S. Broecker*[D]

[A]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA.
[B]School of Molecular Sciences, Arizona State University, Tempe, AZ 85287, USA.
[C]School of Sustainable Engineering and the Built Environment, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ 85287, USA.
[D]Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA.
[E]Corresponding author. Email: anbar@asu.edu

Environmental context. We are entering an epoch – the Anthropocene – in which human activity is changing the face of the planet. To stabilise climate, we may consider deliberate intervention into Earth's systems, on a global scale. Responsible stewardship requires that we develop a safe, economic and environmentally acceptable means of sequestering CO_2 from the atmosphere.

Abstract. The Anthropocene is an evolutionary transition to an epoch in which human activity has become one of the most important Earth systems. To successfully navigate this transition, we must develop a fully integrated environmental science that anticipates the responses of the human system alongside other Earth systems. Applying this perspective to climate change, the signature global environmental challenge in the early part of the Anthropocene, we analyse the ongoing failures of climate policy and the prospects for serious investment in technologies to remove CO_2 from the atmosphere.

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Pragmatic planetary perspective

We live in the Anthropocene – the Age of Humans.[1] In this new epoch, human activity is emerging as one of the most important Earth systems, rivalling and stressing the climate system and other systems that govern our planet's habitability.[2–15]

The advent of the Anthropocene is often viewed as an unnatural event, as though humanity is separate from the natural system in which we evolved. However, the Anthropocene is more realistically viewed as a natural transition, in that it results from the most recent biological innovation in the ~4-billion-year evolution of life on Earth – the evolution of conscious, tool-using intelligence – and the consequent rise of a global, technological civilisation.

Like many evolutionary innovations, this one is disruptive to Earth's pre-existing systems.[16] The same was true of the invention of O_2-producing photosynthesis – perhaps the first planetary pollution crisis – that began to permanently transform the atmosphere by 2.4 billion years ago.[17,18] So, too, the emergence of multicellular organisms, of skeletal animals and of land plants in the ensuing eons. In coming decades, as we begin to characterise the billions of Earth-like worlds that are now thought to exist in our galaxy,[19] we will probably find that disruptive innovations are typical of life-bearing worlds.

A consequence of this planetary perspective is that we cannot aim to 'fix' the problems of the Anthropocene in the sense of returning planet Earth to an idyllic pre-Anthropocene state. Doing so is a practical and moral impossibility in a world populated by seven billion tool-using humans determined to forge better lives for themselves and their children. The evolutionary genie will not go back in the bottle.

Instead, as Earth's first intelligent planetary species, we have the opportunity to learn how to manage the complex, interwoven systems of 'spaceship Earth' so as to maintain a 'safe operating space' for human civilisation.[20] To do so, we must develop an integrated approach to environmental science that considers humans as a natural, integral, permanent and constantly evolving component of Earth's biogeochemical systems. In this view, pragmatic understanding of this 'human system' – including insights drawn from history and the social sciences – must be integrated with pragmatic understanding of the traditional Earth systems. This is a daunting challenge that we barely understand and for which environmental scientists are poorly prepared.

Below, we apply this perspective to the particular case of global climate change, the signature global environmental challenge of the early part of the Anthropocene (in the sense of Crutzen[1] and Zalasiewicz et al.[21]).

The coming climate crisis

Our inadequacies as planetary stewards are manifested in the well-documented exponential changes that characterise the Anthropocene.[22] Poor management usually culminates in crisis, and so, based on the way the Anthropocene has been managed so far, it will likely unfold as a series of crises that we will only confront when public opinion crosses key tipping points, probably lagging behind, rather than leading, tipping points in biogeochemical systems. This is an especially likely scenario for climate change driven by anthropogenic CO_2 emissions.

Atmospheric CO_2 levels – which recently crossed a global average value of 400 ppm (see http://scrippsco2.ucsd.edu, accessed 18 April 2016) – are increasing despite a broad scientific consensus that anthropogenic CO_2 plays a key role as a climate driver and that the pace of human emission of CO_2 is historically unprecedented.[23] Reasoned and plausible arguments suggest that the present trajectory is dangerous (e.g. Hansen et al.,[24] Rockström et al.[25]), but despite innovations in technologies and practices, we have not deployed them at the scale needed to change, let alone reverse, these trends (e.g. Friedlingstein et al.[26]).

The window for a smooth solution is closing rapidly. A 2 °C warming target, relative to pre-industrial climate, has been widely promulgated as a threshold beyond which lie harmful climate consequences (the United Nations Framework, UNFCCC[27]), and was reaffirmed at the recent United Nations Climate Change Conference ('COP21') in a remarkable consensus agreement among 196 nations. Policymakers have sought to avert danger by encouraging a gradual transition to non-fossil energy resources and more efficient energy use (e.g. Deetman et al.[28]). However, models suggest that it is already too late to avoid global warming of 1.5 °C even if we immediately begin to reduce emissions by 5 % per year,[29] a rate deemed by many economists to be the plausible maximum rate of transition.[30] A global average warming target of 2 °C will become unattainable by such emissions reduction if they do not begin by 2027.[29]

There is little evidence that the industrial nations will curb emissions sharply enough to meet the 2 °C target (e.g. Friedlingstein et al.[26]), despite nearly three decades of sustained and concerted efforts by scientists and others to mobilise the public and national leaders, compelling national security interests that favour a shift away from rare and vulnerable fossil fuel resources, and cost–benefit arguments that favour early action. Under present trends and policies, USA energy-related CO_2 emissions are forecast to decline on average only ~0.2 % $year^{-1}$ from 2005 to 2040.[31] Proposed policies such as the US Environmental Protection Agency's (EPA) Clean Power Plan,[32] which would require emissions by US power plants to fall by only ~1.2 % $year^{-1}$, are sufficiently contentious that their implementation is uncertain. Globally, many countries are struggling to keep on track with voluntary pledges made in the 2010 Cancún Agreements,[33,34] which are in any case inadequate to avoid the 2 °C threshold (e.g. Höhne et al.[35]). China, which now leads the world in total CO_2 emissions, has pledged only to cap emissions increases by 2030.[36] Hence, the odds are very long that we will begin the necessary reductions by 2027.

By definition, the timing of crises cannot be predicted, but we can forecast when key milestones will be reached under different scenarios using the simple but illustrative model of Stocker.[29] For example (Fig. 1), if global carbon emissions begin to decline at 0.2 % $year^{-1}$ in 2020 – the same pace forecast for the USA – after rising at a rate of 1.8 % $year^{-1}$ from now until then, the 2 °C peak warming threshold will become unavoidable ~2050, and peak warming of 3 °C becomes unavoidable by ~2100. Thus, if warnings about the dangers of the 2 °C threshold are correct, we may cross a tipping point by mid-century.

Ariel D. Anbar is a scientist and educator interested in Earth's past and future evolution as an inhabited world, and the prospects for life beyond. Trained as a geologist and a chemist, Anbar is a President's Professor at Arizona State University, where he is on the faculty of the School of Earth & Space Exploration and the School of Molecular Sciences, and a Distinguished Sustainability Scholar in the Global Institute of Sustainability. The author or co-author of over 100 refereed papers, Anbar directed ASU's NASA-funded Astrobiology Program from 2009 to 2015. He now oversees the PlanetWorks initiative dedicated to understanding and preserving Earth's habitability in the Anthropocene. He is a graduate of Harvard (A.B. 1989) and Caltech (Ph.D. 1996). Anbar is a Fellow of the Geological Society of America, which awarded him the Donath Medal in 2002. He was recognised as an HHMI Professor in 2014, and elected a Fellow of the Geochemical Society and the European Association of Geochemistry in 2015.

Stephen Romaniello is a research scientist at Arizona State University. He completed his B.A. and M.Sc. at Cornell University followed by his Ph.D. at Arizona State University. His interests include biogeochemistry, isotope geochemistry, cosmochemistry and climate issues. He currently manages the W.M. Keck Laboratory for Environmental Biogeochemistry and the Isotope Cosmochemistry and Geochronology Laboratory at Arizona State University, overseeing a large group of Ph.D. students and post-docs. He is currently serving as lead research scientist for Arizona State University's PlanetWorks Initiative, which focuses on transformative solutions to large-scale environmental and climate challenges.

Braden R. Allenby is Lincoln Professor of Engineering and Ethics; President's Professor of Civil, Environmental, and Sustainable Engineering, and of Law; Founding Chair of the Consortium for Emerging Technologies, Military Operations, and National Security; and Founding Director of the Center for Earth Systems Engineering and Management, at Arizona State University. Dr Allenby received his B.A. from Yale University, his J.D. and M.A. (economics) from the University of Virginia, and his M.Ss. and Ph.D. in Environmental Sciences from Rutgers University. He is past President of the International Society for Industrial Ecology and an AAAS Fellow and a Fellow of the Royal Society for the Arts, Manufactures & Commerce. His areas of expertise include emerging technologies, especially in the military and security domains, Design for Environment, industrial ecology, telework and net-centric organisations, transhumanism, and earth systems engineering and management. In 2008 he was selected by the Carnegie Foundation as 2008 Arizona Professor of the Year.

Wallace S. Broecker received his Ph.D. from Columbia University in 1958 and is presently the Newberry Professor at Columbia University's Lamont–Doherty Earth Observatory. His research is directed toward the role of the oceans in climate change, and he developed the idea of a global 'conveyor belt' linking the circulation of the global ocean. Over the course of his scientific career Wally has made major contributions to the science of the carbon cycle and the use of chemical tracers and isotope dating in oceanography. Prof. Broecker received the Vetlesen Prize (Lamont–Doherty Earth Observatory and the G. Unger Vetlesen Foundation) in 1987 and the Crafoord Prize (Royal Swedish Academy of Sciences) in 2006 for his research into the global carbon cycle.

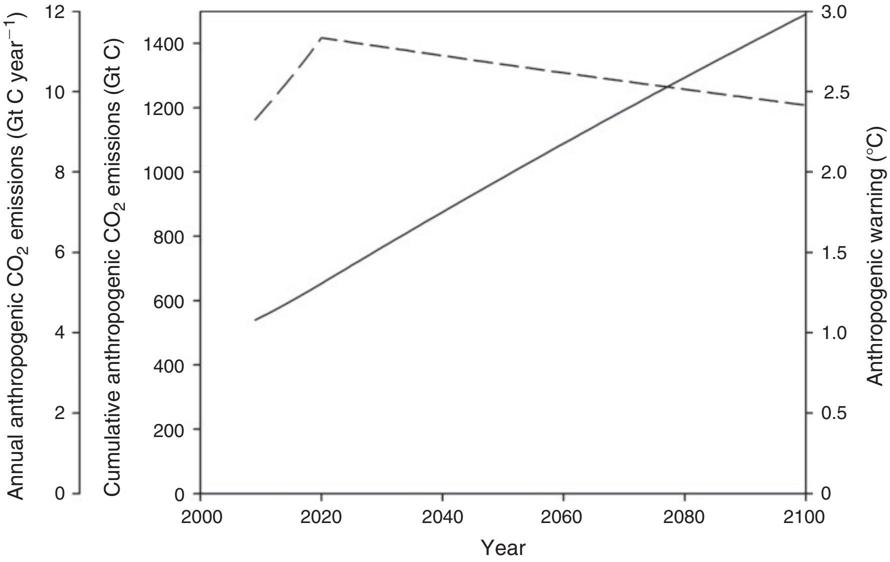

Fig. 1. Annual (dashed line) and cumulative (solid line) anthropogenic CO_2 emissions. Long-term 'peak' climate warming, which is nearly linearly proportional to cumulative anthropogenic CO_2 emissions, is plotted on the right axis assuming a climate sensitivity of 2 °C per 1000 Gt C (Allen et al.[37]). Curves are shown for a hypothetical 'minimal management' scenario, according to which total annual CO_2 emissions decline at a rate of 0.2 % $year^{-1}$ after 2020, similar to the rates forecast for the USA.[31] Cumulative CO_2 emissions pass 1000 Gt C in 2050 and 1500 Gt C in 2100, committing the planet to peak warming of 2 and 3 °C in 2050 and 2100 respectively.

Importantly, these estimates may be conservative, especially in the long run. They assume median values of parameters that are uncertain (e.g. Allen et al.[37]), and may not include 'slow' feedback processes, such as decrease in ice cover, that become important on a timescale of centuries.[38]

Human system failure

Our failure to manage CO_2 emissions does not reflect inadequate understanding of Earth's biogeochemical systems. To be sure, uncertainties in the carbon cycle and climate response create forecasting challenges that complicate the development and implementation of effective policies to reduce CO_2 emissions (e.g. Meinshausen et al.,[39] Victor and Kennel[40]). However, our basic limitation as planetary stewards in the early Anthropocene will likely be that we did not adequately appreciate the complexities of the human aspect of Earth's systems.

These complexities seemed reasonably simple and manageable when an earlier generation of scientists and other leaders averted catastrophic damage to the O_3 layer by anthropogenic chlorofluorocarbons (CFCs). In that case, the global community evolved from scientific hypothesis to effective policy response within a generation. Drawing on this successful precedent, the Montreal Protocol, which led to reduction of CFC emissions, inspired the Kyoto Protocol and ongoing international efforts to reduce emissions of anthropogenic CO_2 (e.g. Canan et al.[41]).

Viewing the CO_2 problem as analogous to CFCs makes sense from a traditional biogeochemical perspective because the scientific foundations of the CO_2–climate connection are easier to understand than the CFC–O_3 connection. It is not surprising that the effect of CO_2 as a greenhouse gas was correctly outlined by Svante Arrhenius nearly a century before Sherry Rowland and co-workers called attention to the effect of CFCs on O_3![42,43]

However, the analogy breaks down when considering humanity as an integral part of the Earth system. CO_2 emission stems from broad human energy usage patterns and fossil fuel dependencies that are vastly more entrenched and difficult to modify than the much more limited uses of CFCs. The time required to re-engineer vast swaths of our energy and transportation infrastructure is a source of inertia in the human system that is as important as any time constant in the climate system. More problematic are the feedbacks arising from economic and political factors that are extraordinarily complex. Further, these human factors interact in complex ways with a climate system that does not evolve monotonically. For example, the possibility that growth in global average temperature slowed over the past ~15 years despite steady increase in atmospheric CO_2 emboldened those who question the scientific consensus, setting back attempts to formulate emission control policies.

Recognising such problems, Victor and Kennel[40] argued that the 2 °C temperature threshold is an ineffective managerial construct, and proposed other metrics to guide policymakers in controlling CO_2 emissions. However, we suggest the problem is more fundamental. If the accumulation of CO_2 in the atmosphere is a qualitatively different challenge in Earth systems management than the accumulation of CFCs, it should not be a surprise that a focus on emissions reduction alone, even if technically sensible and conceptually straightforward, is proving to be an inadequate managerial strategy.

Facing the future

Pulling back from the brink will likely require not only elimination of emissions but also that we eventually establish a regime of net *negative* emissions of CO_2, in which we actively remove CO_2 from the atmosphere (e.g. Keith et al.[44]). The prospect of direct intervention in the climate system is radical and deeply unsettling to many, but is receiving increasing attention, such as in a recent pair of reports issued by the US National Research Council (NRC).[45,46] Why?

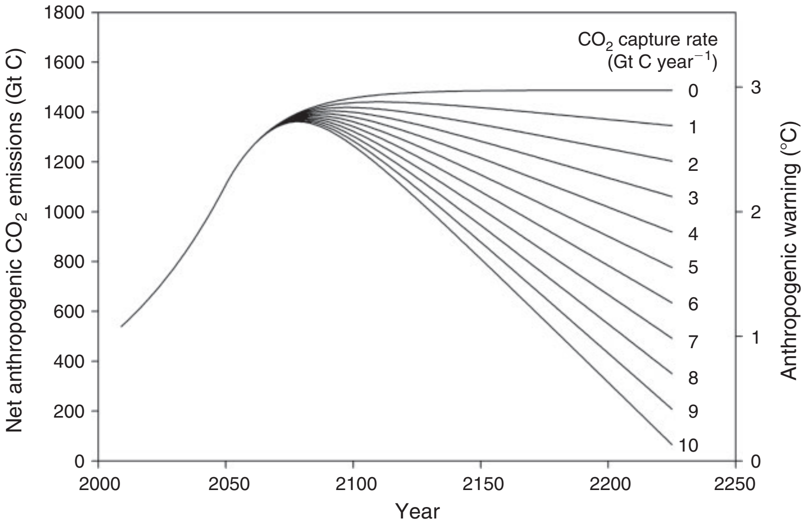

Fig. 2. Net integrated CO_2 emissions for a scenario in which present emission rates continue to increase at 1.8 % year^{-1} until a threshold in public opinion is reached in 2050. Thereafter, global CO_2 emissions rapidly decrease at 5 % year^{-1}. Each line depicts the effect on anthropogenic warming of atmospheric CO_2 capture at the indicated rate. For all scenarios, atmospheric CO_2 capture begins in 2050, gradually ramps up to the maximum rate in 2080, and continues at the maximum rate through 2200. The right axis shows peak anthropogenic warming calculated from cumulative net CO_2 emissions, as in Fig. 1. Calculations are based on the model of Stocker,[29] with the addition of a term for CO_2 capture.

First, we must recognise that long-term 'peak' climate warming is nearly linearly proportional to the total emitted amount of anthropogenic CO_2.[37] Thus, to manage anthropogenic climate change, we primarily need to manage the total inventory of emitted anthropogenic CO_2. Second, we need to recognise that long-term (geologic) sinks for CO_2 operate so slowly that the total inventory of emitted anthropogenic CO_2 partitioned into the atmosphere, shallow oceans and biosphere – CO_2 sinks that equilibrate on the timescale of a few decades – will remain essentially constant on a timescale of centuries following the cessation of anthropogenic CO_2 emissions (e.g. Lowe et al.,[47] MacDougall et al.,[48] Zickfeld et al.[49]).

The combined implication of these two points is that even rapid emission reductions will not be able to undo the damage of past, accumulated emissions. For example, in Fig. 2, curve 0 shows the trajectory for a plausible but hypothetical scenario in which emissions continue to grow at the present rate of 1.8 % year^{-1} until a tipping point in public awareness is reached in 2050, after which emissions decline at a rate of 5 % year^{-1}. Total anthropogenic CO_2 emissions level off at 1487 Gt C by c. 2150, when CO_2 emissions have dwindled to nothing. Yet, even in this scenario, we will have committed ourselves to long-term warming of ~3 °C because we were too slow to begin the process of reducing emissions.

It follows that we may soon pass into a regime in which the *only* way to avoid exceeding the 2 °C threshold, or to minimise the duration of time spent above this limit, will be to deliberately intervene in the global climate system, commonly referred to as 'geoengineering'. Although such measures seem extreme at present, the potential consequences of the present trajectory lead to their serious consideration. At present, two types of interventions have been proposed: direct mitigation of warming by managing Earth's solar radiation budget and removal of CO_2 from the atmosphere.

Solar radiation management (SRM), such as by deliberate injection of sulfate aerosols into Earth's stratosphere, looms large in these geoengineering discussions. The albedo-increasing properties of sulfate aerosols are well understood, and their production and distribution do not exceed present technologies. Therefore, severe climate effects might tempt future policymakers to implement SRM to moderate global average temperatures.

However, there are many reasons to be wary of SRM[46,50]: the unintended planetary consequences of large-scale injection of sulfate into the atmosphere are unknown, SRM does not reduce the problem of CO_2-induced ocean acidification, and SRM is only effective as long as 'treatment' is continued, potentially creating a dangerous dependency on intervention if CO_2 continues to accumulate. The environmental risks are such that SRM proposals been referred to as 'barking mad' by a coauthor of the NRC reports (Pierrehumbert[51]).

Alternatively, it is hypothetically possible to capture CO_2 from the atmosphere and sequester it at significant rates using several approaches (e.g. Keith et al.,[44] Lenton,[52] Lackner,[53] Lackner et al.,[54] Rau,[55] Schuiling and Krijgsman,[56] Strand and Benford[57]). Doing so would augment the natural rate of CO_2 removal in the next 2 centuries, much as we accelerated the rate of CO_2 emissions in the past 2 centuries. So-called 'carbon dioxide removal' (CDR) is really a process of 'waste clean-up' to rebalance the carbon cycle. Consequently, concerns about CDR centre on physical limits and costs of various approaches (e.g. Matthews[58]), more than on environmental risk.[45,50]

The rate of CDR needed to clean up the mess humans have created is easily calculated. As an example, we consider the emission abatement scenario above with the addition of various rates of direct CO_2 capture from air, ranging from 1 to 10 Gt C year^{-1}, which begin in 2050, ramp up to their maximum rate by 2080, and continue at the maximum rate through 2200 (Fig. 2).

The maximum rate of direct capture considered here, 10 Gt C $year^{-1}$, is similar to the present rate of anthropogenic emissions. At this maximum rate, an amount of CO_2 equal to the total historical emissions of anthropogenic CO_2 would be captured by the year 2210. Of the various CDR approaches that have been considered – including ocean iron fertilisation, ocean carbonate addition, biochar production, accelerated mineral weathering, afforestation and other changes in land-use management – direct air capture combined with storage in geological reservoirs is likely the most effective approach.[58,59]

To be sure, such simple models understate the scope of the challenge! Leaving aside logistical and cost issues, CO_2 released from warming permafrost may make a significant additional contribution of CO_2 that would need to be recaptured in order to prevent warming in both zero- and negative-emissions scenarios.[48,60] Early modelling estimates of the magnitude of this additional carbon pool increase approximately linearly from 300 to 1000 Gt C as peak warming increases from 1.8 to 8 °C. For negative-emissions scenarios, this effect could potentially increase the total amount of CO_2 to be recaptured by 118–180 %.

Additionally, the effects of global climate change may not be fully reversible. Several recent studies agree that changes in the Earth's surface temperature, soil moisture, precipitation, cloud cover and surface ocean pH all exhibit only low levels of hysteresis on decadal time scales.[61–64] However, simulations suggest that warming effects on ice sheets and ecosystems may not be reversible, or are only reversible on millennial time scales.[60,65] So, it is likely that even in the most optimistic scenario, there is no going back to a pre-industrial Earth.

Despite these challenges, CDR may soon be the only way to pull atmospheric CO_2 back below dangerous thresholds that planet Earth is rapidly approaching. The question we may soon face is not whether or not CDR is possible or desirable, but whether or not it will be considered practical by the public and policymakers.

Human system response

If the more alarming climate forecasts are correct, the public and policymakers in the coming decades will need to strike a balance between investments in adaptation to the consequences of increasing climate change, CO_2 emissions reductions and mitigation through climate intervention. CDR has generally been discounted as a significant part of this climate response portfolio because of its costs. We are not convinced that these analyses correctly gauge the human system response to future climate change.

The typical framework of the cost debate envisions establishment of a carbon emissions market, according to which CO_2 removal will only happen if the cost per ton of carbon removed from the atmosphere imposes only a small additional cost per ton of fossil fuel carbon burned. Because no prototype CDR system has been designed and tested at scale, opinions on the cost of air capture range widely. Two groups actively researching technologies for chemical capture using amine-based resins (Klaus Lackner's group at Arizona State University and Peter Eisenberger's group at Stanford Research Institute) are convinced that when done on a large scale, it will cost less than US$100 per tonne of CO_2 (e.g. Lackner[53]). Others claim prices 6 to 10 times higher (e.g. House et al.[66]). If those working on the technology are correct, then it could be done for less than US$1 per gallon (US$0.26 per litre) add-on to the price of gasoline (petrol). If the critics are correct, the add-on would be a much higher US$6–10 dollars per gallon (US$1.56–2.60 L^{-1}), which is unworkable if passed along to consumers at the pump. Clearly, it would be prudent to attempt to settle this debate by accelerating research into air capture technologies.

However, even if this debate cannot be settled, or if the cost of CDR indeed turns out to be at the high end of the range of estimates, the assumption underlying the preceding framework is that the public will continue indefinitely to assign a low value to combatting climate change. This assumption will be shattered if increasing consequences of climate change turn widespread scepticism to widespread anxiety. The result could be a willingness to shoulder much higher costs through general taxation and directed government spending – the funding mechanisms used to finance national defence – than would be tolerated through a carbon tax, gas tax or other use-related approaches.

What costs might an anxious public be able to bear? Consider that annual defence spending in the US, ~US$530 billion in 2014, is comparable with the annual cost of removing 5 Gt C $year^{-1}$ at a price of US$100 t^{-1}. Approximately this annual level of expenditure, adjusted for inflation, was sustained by the USA throughout the post-WWII period. Even higher levels of expenditure are plausible. For example, what if this calculation underestimates the price of CO_2 removal by a factor of 10, resulting in a cost of ~US$5 $\times 10^{12}$ $year^{-1}$? This figure is still <10 % of today's global gross domestic product (GDP), and <2 % of projected global real GDP in 2050.[67] So, even at the high end, the costs of CDR are within what might be tolerated if future events cause the public to make climate mitigation a high priority, driving international collaborative action.

At the same time, an anxious public may make poor decisions if they have no other options. One concern is that policymakers faced with public alarm may opt for a risky SRM scheme if CDR technologies are still only an idea in the laboratory. Thus, an attempt to develop CDR technologies is necessary to ensure that a workable alternative to SRM, with less environmental risk, is in place *before* there is a shift in public attitudes. Because it will take a decade or so to produce a reliable capture system, we should undertake this development and have it on the shelf so that it is ready for manufacture and deployment if the situation should arise.

Conclusion

The world has yet to face up to the challenge of halting the ongoing rise in atmospheric CO_2. Because the climate consequences of a doubling or perhaps even tripling of atmospheric CO_2 will be manifold and largely negative, it seems inevitable that deliberate intervention in the climate system will be seriously contemplated, alongside adaptation and emissions control strategies. We should not hesitate to develop a safe, economic and environmentally acceptable means of sequestering CO_2 from the atmosphere.

Deliberate environmental intervention on this global scale is still unimaginable to most, but human beings long ago accepted as routine interventions on local and regional scales that were unimaginable to our ancestors. We accept that humans are a fully integrated part of ecosystems at these scales, and that we have a responsibility to mitigate our impact when it cannot be minimised. Similarly, we should ensure that our descendants in the Anthropocene routinely think of humans as a fully integrated part of the global Earth system, with the responsibility to mitigate the global biogeochemical cycles that we perturb.

Acknowledgements

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