Received: 25 March 2019 | Revised: 28 May 2019 | Accepted: 6 June 2019

DOI: 10.1002/ppp3.10066

OPINION

Plants People Planet PPP Open Access

Can plants help us avoid seeding a human-made climate catastrophe?

David J. Beerling

Department of Animal and Plant Sciences, Leverhulme Centre for Climate Change Mitigation, University of Sheffield, Sheffield, UK

Correspondence
David J. Beerling, Department of Animal and Plant Sciences, Leverhulme Centre for Climate Change Mitigation, University of Sheffield, Sheffield, S10 2TN, UK.
Email: d.j.beerling@sheffield.ac.uk

Funding information
Leverhulme Trust Research Centre, Grant/Award Number: RC-2015-029

Societal Impact Statement

Human-made climate change places the future of the planet in peril. Rapid greenhouse gas emissions over the past few decades already commit Earth to a warmer climate state and lock-in future extinctions. I consider what steps might be taken to protect the climate and the future of the biosphere by drawing on our understanding of the Devonian rise of forests. At stake is nothing less than the future of humanity and the fate of species we are fortunate enough to share the planet with.

Summary

Drastic phase down of our carbon dioxide (CO_2) emissions from burning fossil fuels within decades will likely be insufficient to avoid seeding catastrophic human-caused climate change. We have to also start removing CO_2 from the atmosphere, safely, affordably and within decades. Technological approaches for large-scale carbon removal and storage hold great promise but are far from the gigaton-scale required. Enhanced chemical weathering of crushed silicate rocks and afforestation are proposed CO_2 removal approaches mimicking events during the Devonian rise of forests that triggered massive CO_2 drawdown and the great late Palaeozoic cooling. Evidence from Earth's history suggests that if undertaken at scale, these strategies may represent key elements of a climate restoration plan but will still be far from sufficient. Climate protests by the world's youth are justified. They recognize the urgency of the situation and the intergenerational injustice of our time: current and future generations footing the immense economic and ecological bill for damaging carbon emissions they had no part in and which world leaders are failing to limit.

KEYWORDS

carbon dioxide removal, chemical weathering, climate change, Earth history, reforestation

1 | INTRODUCTION

The amount of carbon dioxide (CO_2) released into the atmosphere from fossil fuels and industry is at a staggering all-time high of ~36 billion tonnes (Gt, 10^9) annually, having risen every decade since the 1960s (Le Quere et al., 2018). Cumulative emissions from human activities since the onset of the pre-industrial era have raised the atmospheric concentration of CO_2, and other major greenhouse gases (GHGs), to levels unprecedented in human history.

What's more, the concentration of atmospheric CO_2 and other GHGs has risen so rapidly over the past few decades that Earth's temperature has yet to adjust fully to the new warmer climate they dictate. This means that even if we could magically stop our CO_2 emissions from fossil fuels overnight, we have already committed Earth to transition to a warmer climate (Hansen et al., 2013). Global temperatures have risen by more than 1°C since the 1970s (IPCC, 2018). How much more warming is 'in the pipeline'? In the near-term, we are practically guaranteed another 0.5°C as the climate system equilibrates to the increased radiative forcing from rising concentrations of GHGs, with slow amplifying climate feedbacks likely to add another 1.0, 1.5°C or worse. In December 2015, over 190 nations worldwide signed up to the United Nations Framework Convention on Climate Change Paris Agreement with the aim of holding the increase in global average temperate to below 2°C and pursue efforts to limit the increase to 1.5°C, but without a legal mandate for enforcement (UNFCCC, 2015). Given the current situation, even a lenient 2°C target now looks wildly optimistic, and significant temperature 'overshoots' seem more likely, with potentially disastrous consequences for the planet (IPCC, 2018; Obersteiner et al., 2018).

International scientific organizations, including the UK's Royal Society (Royal Society, 2018), the National Academy of Sciences in the United States (National Academy of Sciences, 2015, 2018) and the United Nations Intergovernmental Panel on Climate Change (IPCC, 2018), acknowledge that we have to start removing CO_2 from the atmosphere, safely, affordably and within a decade or two. At the same time, we need to transform fundamentally our global energy systems by replacing carbon-intensive fossil fuels with low-emission or carbon-free alternatives to slow and then halt carbon emissions (Davis et al., 2018). And, every year we delay emissions reductions, tens of billion of tonnes of CO_2 are released into the atmosphere, making an already herculean task increasingly difficult (Hansen et al., 2013, 2017; Stocker, 2013).

2 | ENTER THE KINGDOM OF PLANTS: MAKING EDEN REDUX

Lessons from Earth's history during the greening of the continents have relevance to our current situation (Figure 1; Beerling, 2019). Evidence from Earth history indicates that hundreds of millions of years ago, during the Devonian Period (415–360 million years ago), plants 'bioengineered' a cooler climate as the evolutionary appearance of trees, and the subsequent spread of deep-rooting forests lowered Palaeozoic atmospheric CO_2 levels by 90% (Berner, 1997, 1998). The mechanisms for this drastic long-term CO_2 decline and climatic descent towards the Permo-Carboniferous ice-age are well understood. As root systems evolved to become larger and more complex, they increased the surface area of the soil–root interface and exploited larger volumes of soil for anchorage, water and nutrient uptake (Beerling & Berner, 2005; Berner, 1998). Through these and other biogeochemical impacts, trees accelerated the chemical breakdown of silicate rocks (termed weathering), liberating base cations and forming dissolved bicarbonate in the process. Eventually, transport of the weathering products via surface runoff to the oceans resulted in long-term carbon storage (Berner, 1997, 1998). By accelerating the chemical weathering of silicate rocks, and locking up recalcitrant carbon as the great Carboniferous coal measures formed, tree evolution can be viewed as an engine driving late Palaeozoic cooling. This remarkable episode in the evolutionary history of plant life saw Earth transition to a forested planet, and entrain self-reinforcing (or positive) feedbacks whereby bigger trees → deeper roots → faster weathering → greater nutrient release → bigger trees → atmospheric carbon dioxide removal → cooler climate (Algeo & Scheckler, 1998; Beerling, 2007, 2019; Beerling & Berner, 2005; Berner, 1997, 1998).

It may be possible to mimic those processes to remove CO_2 from the atmosphere by dressing the soils of agricultural and forestry landscapes with crushed rapidly weathering silicate rocks, such as basalt (Beerling et al., 2018; Haque, Chiang, & Santos, 2019; Kantola, Masters, Beerling, Long, & DeLucia, 2017; Zhang, Kang, Wang, & Zhu, 2018). The approach harnesses the power of plants, their root-associating symbiotic microbiota and corrosive soil pore waters, to

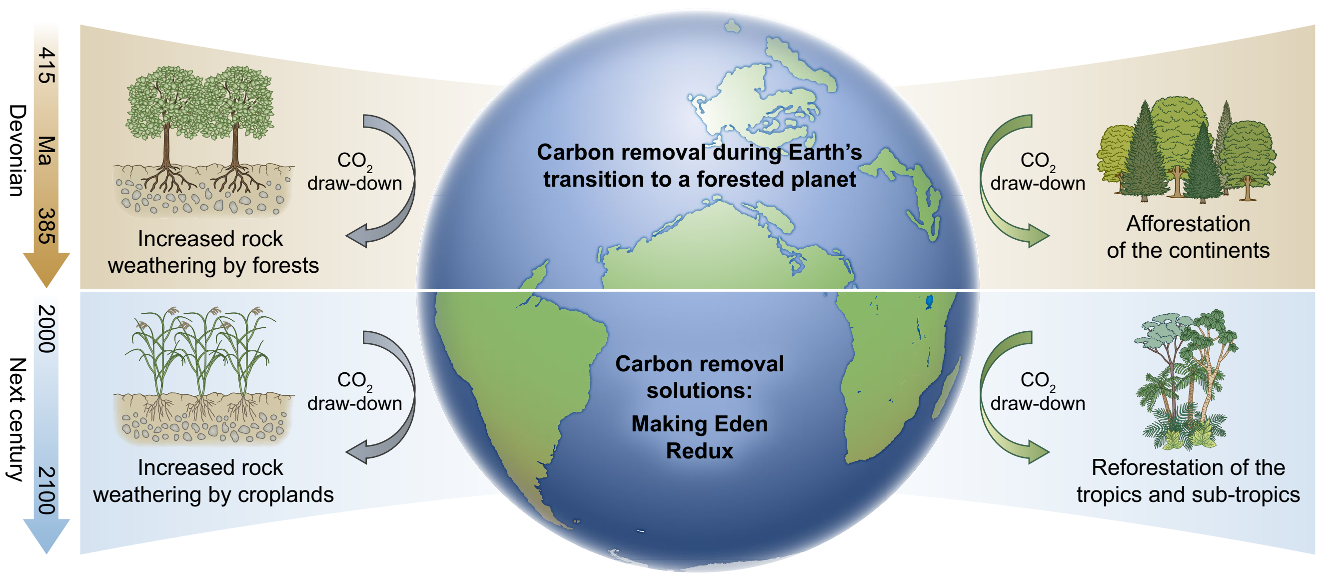

FIGURE 1 Symmetry in categories of carbon sequestration processes during Earth's transition to a forested planet through the Devonian and those proposed for future climate change mitigation

chemically break down rock dust and capture carbon (Zhang, et al. 2018; Kantola et al., 2017). Alkaline silicate rock dust minerals are immediately available and may be suitable for diverse crops and forestry initiatives. Making biogeochemical soil improvements in this way may also boost yields and harvests by adding plant-essential nutrients and helping reverse soil acidification.

At the same time, an alarming soils crisis is unfolding (Banwart, 2011). According to the United Nations (2017), agricultural top soils that provide food security for billions of people are disappearing at a rate of 25 Gt/year. Conservation agriculture (which includes minimum tillage) addresses this problem by reducing mechanical soil disturbance and adding organic carbon back to soil. Implementation is increasing, and conservation agriculture is being practiced on about 180 million hectares of cropland, ~12.5% of croplands globally, with adoption becoming widespread throughout North and South America and Europe (Kassam, Friedrich, & Derpsch, 2019). Yet, more needs to be done. And, both large-scale CO_2 removal and rebuilding of our rapidly disappearing top soils that underpin food security could be addressed with restorative soil management practices involving crushed natural and artificial silicate rocks to improve global carbon and nutrient cycles. The joint requirement for saving our climate and soils has congruence, in terms of the magnitude of the problem and solution, and this could help incentivize action and increase feasibility.

Humans have put ~1.53 billion hectares of land to the plough over the past century (Foley et al., 2011), releasing a cumulative ca. 133 Gt C from soils in the process (Sanderman, Hengl, & Fiske, 2017), and application of crushed rock to farmland could exploit existing logistic infrastructure. Potential also exists for increasing carbon sequestration in agricultural soils through changes in land management practices (Minasny et al., 2017; Zomer, Bossio, Sommer, & Verchot, 2017), including addition of biochar formed by pyrolysis of biomass (Woolf, Amonette, Street-Perrott, Lehmann, & Joseph, 2010), with possible benefits for food security. However, as with most large-scale CO_2 removal proposals, complex cultural, economic and political constraints raise uncertainties over their effectiveness (Amundson & Biardeau, 2018).

We could also develop allied strategic carbon removal initiatives by undertaking reforestation of forested lands once cleared for agriculture, and afforestation of new areas (Lewis, Wheeler, Mitchard, & Koch, 2019), again mimicking the ancient Devonian 'greening of land' when forests first spread across the continents (Figure 1; Beerling, 2019). But the case is far from straightforward. Ambitious global tree restoration opportunities that could promote carbon sequestration with multiple benefits (Bastin et al., 2019) require feasibility assessment, costings and careful carbon accounting, and must avoid potential conflicts with the rising demand for food. As part of The Bonn Challenge, an international plan to restore 350 million hectares of forest by 2030, 43 countries throughout the tropics and subtropics have already committed to replanting 300 million hectares of degraded land (The Bonn Challenge, 2011). However, if reforestation occurs through planting of commercial trees that are regularly harvested every 10–20 years, much of the CO_2 captured will be returned back to the atmosphere. More effective would be to encourage natural forest regeneration in the tropics to lock-up CO_2 in forest biomass and soils (Lewis et al., 2019). Undertaken across a sufficiently large area of the globe, restoration of degraded forested ecosystems has the potential to sequester another few billion tonnes of CO_2 by 2100, although verifying increases in tropical forest carbon stocks may prove challenging (Erb et al., 2018). It also requires careful assessment of possible indirect cooling feedbacks via changes in atmospheric chemistry (Popkin, 2019).

3 | CHALLENGES AHEAD

To be absolutely clear, none of these making eden redux carbon capture measures represent a sufficient climate restoration plan. Bringing the atmospheric CO_2 concentration back down to an estimated safe concentration of ~350 ppm (Hansen et al., 2008) requires immediate action to phase down emissions, and a wider portfolio of carbon removal techniques to scrub sufficient amounts of carbon from the atmosphere each year. Yet, these technologies are immature and need multibillion dollar investment to move them from the lab to pilot demonstrations to determine what can scale massively. Erik Solheim, previous Executive Director, the United Nations Environment Programme, recently issued a call to arms here, '*if we invest in the right technologies, ensuring that the private sector is involved, we can still meet the promise we made to our children to protect their future. But we have to get on the case now*' (UN News, 2017).

Right now, carbon removal strategies look like an expensive option for helping to slow the pace of climate change (Hansen et al., 2017) and we must hope that as the engineering challenges are solved, costs fall precipitously as seen in other markets, such as solar energy, to catalyse carbon capture. Without emissions reductions combined with a suite of carbon removal efforts, we will face the profound consequences—growing climate impacts including intensifying droughts, heat-waves, storms, ice-sheet melt and multi-metre sea-level rise flooding coastal regions threatening displacement of hundreds of millions of people (Clark et al., 2016). Not to mention a biosphere in peril (Hansen et al., 2013; Lovejoy & Hannah, 2019; Treves et al., 2018), as human activities prime the engine of species extermination and threaten to seal the fate of biological diversity for millions of years (Beerling, 2019). This is the intergenerational injustice of our time: current and future generations footing the immense economic and ecological bill for damaging carbon emissions they played no part in, and which threaten to wreck the planet by initiating slow climate feedbacks and irreversible climate change on timescales relevant to human society (Hansen et al., 2013, 2017).

Our current climate crisis is urgent and unfolding at a time when global food demand will need to more than double before the end of the century (Godfray et al., 2010). Can we stabilize the climate, preserve the wonderful diversity of life on Earth and sustainably feed a crowded planet, without collateral environmental damage? Reducing GHG emissions from agriculture without compromising food security has to be a priority. Revisiting natural processes of carbon sequestration that occurred during Earth's transition to a forested planet offers pointers for delivering on this grand challenge. With the collective moral failure of world leaders to act so far, it is hardly surprising that young people worldwide are bravely striking for action on climate change (Hagedorn et al., 2019) supported by thousands of scientists (The Guardian, 2019). At stake is nothing less than the future of humanity and the fate of species we are fortunate enough to share the planet with.

ACKNOWLEDGEMENT

I gratefully acknowledge funding through a Leverhulme Trust Research Centre Award (RC-2015-029).

ORCID

David J. Beerling https://orcid.org/0000-0003-1869-4314

REFERENCES

Algeo, T. J., & Scheckler, S. E. (1998). Terrestrial-marine teleconnections in the Devonian: Links between the evolution of plants, weathering processes, and marine anoxic events. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *B353*, 113–130. https://doi.org/10.1098/rstb.1998.0195

Amundson, R., & Biardeau, L. (2018). Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 11652–11656. https://doi.org/10.1073/pnas.1815901115

Banwart, S. (2011). Save our soils. *Nature*, *474*, 151–152. https://doi.org/10.1038/474151a

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., ...Crowther, T. W. (2019). The global tree restoration potential. *Science*, *365*, 76–79. https://doi.org/10.1126/science.aax0848

Beerling, D. J. (2007). *The emerald planet. How plants changed Earth's history*. Oxford, UK: Oxford University Press.

Beerling, D. J. (2019). *Making Eden. How plants transformed a barren planet*. Oxford, UK: Oxford University Press.

Beerling, D. J., & Berner, R. A. (2005). Feedbacks and the coevolution of plants and atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 1302–1305. https://doi.org/10.1073/pnas.0408724102

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., ... Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security. *Nature Plants*, *4*, 138–147. https://doi.org/10.1038/s41477-018-0108-y

Berner, R. A. (1997). The rise of plants and their effect on weathering and atmospheric CO_2. *Science*, *276*, 544–546. https://doi.org/10.1126/science.276.5312.544

Berner, R. A. (1998). The carbon cycle and CO_2 over Phanerozoic time: The role of land plants. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *B353*, 75–82. https://doi.org/10.1098/rstb.1998.0192

Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., ... Plattner, G.-K. (2016). Consequences of twenty-first century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, *6*, 360–369. https://doi.org/10.1038/nclimate2923

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., ... Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*, eaas9793. https://doi.org/10.1126/science.aas9793

Erb, K.-H., Kastner, T., Plutzar, C., Bais, A. L. S., Carvalhais, N., Fetzel, T., ... Luyssaert, S. (2018). Unexpectedly large impacts of forest management and grazing on global vegetation biomass. *Nature*, *553*, 73–76. https://doi.org/10.1038/nature25138

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., ... Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337–342. https://doi.org/10.1038/nature10452

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., ... Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*, 810–818. https://doi.org/10.1126/science.1185383

Hagedorn, G., Kalmus, P., Mann, M., Vicca, S., Van den Berge, J., van Ypersele, J.-P., ... Hayhoe, K. (2019). Concerns of young protesters are justified. *Science*, *354*, 139–140. https://doi.org/10.1126/science.aax3807

Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D. J., ... Zachos, J. C. (2013). Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLoS ONE*, *8*, e81648. https://doi.org/10.1371/journal.pone.0081648

Hansen, J., Sato, M., Kharecha, P., Beerling, D. J., Berner, R. A., Masson-Delmonte, V., ... Zachos, J. C. (2008). Target atmospheric CO_2: Where should humanity aim? *The Open Atmospheric Science Journal*, *2*, 217–231. https://doi.org/10.2174/1874282300802010217

Hansen, J., Sato, M., Kharecha, P., von Schuckmann, K., Beerling, D. J., Cao, J., ... Ruedy, R. (2017). Young people's burden: Requirement of negative CO_2 emissions. *Earth System Dynamics*, *8*, 577–617. https://doi.org/10.5194/esd-8-577-2017

Haque, F., Chiang, Y. W., & Santos, R. M. (2019). Alkaline mineral soil amendment: A climate "stabilization wedge"? *Energies*, *12*, 2299. https://doi.org/10.3390/en12122299

IPCC [Intergovernmental Panel on Climate Change]. (2018) *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Geneva, Switzerland: World Meteorological Organization.

Kantola, I. B., Masters, M. D., Beerling, D. J., Long, S. P., & DeLucia, E. H. (2017). Potential of global croplands and bioenergy crops for climate change mitigation through deployment of enhanced weathering. *Biology Letters*, *13*, 20160714. https://doi.org/10.1098/rsbl.2016.0714

Kassam, A., Friedrich, T., & Derpsch, R. (2019). Global spread of conservation agriculture. *International Journal of Environmental Studies*, *76*, 29–51.

Le Quere, C., Andrew, R., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., ...Arneth, A. (2018). Global carbon budget 2018. *Earth System Science Data*, *10*, 2141–2194.

Lewis, S. L., Wheeler, C. E., Mitchard, E. T., & Koch, A. (2019). Regenerate natural forests to store carbon. *Nature*, *568*, 25–28.

Lovejoy, T. E., & Hannah, L. (Eds.). (2019). *Biodiversity and climate change*. New Haven, CT and London, UK: Yale University Press.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., & Chambers, A., ...Field, D. J. (2017). Soil carbon per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

National Academy of Sciences. (2015). *Climate intervention: Carbon dioxide removal and reliable sequestration*. Washington, DC: National Academy of Sciences.

National Academy of Sciences. (2018). *Negative emissions technologies and reliable sequestration: A research agenda*. Washington, DC: National Academy of Sciences.

Obersteiner, M.,Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., ...Peñuelas, J. (2018). How to spend a dwindling greenhouse gas

budget. *Nature Climate Change*, *8*, 7–10. https://doi.org/10.1038/s41558-017-0045-1
Popkin, G. (2019). The forest question. *Nature*, *565*, 280–282.
Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 9575–9580. https://doi.org/10.1073/pnas.1706103114
Stocker, T. F. (2013). The closing door of climate targets. *Science*, *339*, 280–282. https://doi.org/10.1126/science.1232468
The Bonn Challenge (2011). *The Challenge*. Retrieved from http://www.bonnchallenge.org/content/challenge
The Guardian (2019). School climate strike children's brave stand has our support. Retrieved from https://www.theguardian.com/environment/2019/feb/13/school-climate-strike-childrens-brave-stand-has-our-support
The Royal Society. (2018). *Greenhouse gas removal technologies*. London, UK: The Royal Society.
Treves, A., Artelle, K. A., Darimont, C. T., Lynn, W. S., Paquet, P., Santiago-Ávila, F. J., …Wood, M. C. (2018). Intergenerational equity can help to prevent climate change and extinction. *Nature Ecology and Evolution*, *2*, 204–207. https://doi.org/10.1038/s41559-018-0465-y
UN News. (2017). UN sees 'worrying' gap between Paris climate pledges and emissions cuts needed. Retrieved from https://news.un.org/en/story/2017/10/569672-un-sees-worrying-gap-between-paris-climate-pledges-and-emissions-cuts-needed
UNFCCC. (2015). *The Paris Agreement*. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
United Nations. (2017). *Global land outlook* (1st ed.). Bonn, Germany: United Nations Convention to Combat Desertification.
Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56. https://doi.org/10.1038/ncomms1053
Zhang, G., Kang, J., Wang, T., & Zhu, C. (2018). Review and outlook for agromineral research in agriculture and climate mitigation. *Soil Research*, *56*, 113–122. https://doi.org/10.1071/SR17157
Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports*, *7*, 15554. https://doi.org/10.1038/s41598-017-15794-8

How to cite this article: Beerling DJ. Can plants help us avoid seeding a human-made climate catastrophe? *Plants, People, Planet*. 2019;00:1–5. https://doi.org/10.1002/ppp3.10066