Leverhulme Centre for Climate Change Mitigation (LC^{3}M)

Full publication listing through to October 2025

2025

83) Beerling, D.J., Reinhard, C.T., James, R.H. *et al.* (2025) Challenges and opportunities in scaling enhanced weathering for carbon dioxide removal. *Nat Rev Earth Environ*. https://doi.org/10.1038/s43017-025-00713-7

82) Nelson, P.N., Green, H. & Holden, F. (2025) Comment on 'CO_2 removal with enhanced wollastonite weathering in acidic and calcareous soils'. *Soil Ecology Letters,* **75**(3), 250322. https://doi.org/10.1007/s42832-025-0322-2

81) Cox, E, Low, S., Baum, C.B., Fritz, L., Waller, L., Spence, E., Pidgeon, N. & Bellamy, R. (2025) Carbon removal beyond the trees. *Communications Earth & Environment*, **6**, 253. http://dx.doi.org/10.1038/s43247-025-02226-z

80) Shi, Y., Heald, C. L. & Val Martin, M. (2025) Future anthropogenic land use change impacts on carbonaceous aerosol and implications for climate and air quality. *Geophysical Research Letters*, **52**. https://doi.org/10.1029/2024GL110962

79) Beerling, D.J., Kantzas, E.P., Lomas, M.R., Taylor, L.L., Zhang, S., Kanzaki, Y., Eufrasio, R.M., Renforth, P., Mecure, J-F., Pollitt, H., Holden, P.B., Edwards, N.R., Koh, L., Epihov, D.Z., Wolf, A., Hansen, J.E., Banwart, S.A., Pidgeon, N.F., Reinhard, C.T., Planavsky, N.J. & Val Martin, M. (2025) Transforming US agriculture for carbon removal with enhanced weathering. *Nature*. https://doi.org/10.1038/s41586-024-08429-2

78) Cox, E., Lim, R., Spence, E., Payne, M., Beerling, D. & Pidgeon, N.F. et al (2025) Question-led innovation: public priorities for enhanced weathering research in Malaysia. *Environmental Science and Policy*, 163, 103977. https://doi.org/10.1016/j.envsci.2024.103977

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77) Repke, T., Muller-Hansen, F., Cox, E. & Minx, J. C. (2024). Attention and positive sentiments towards carbon dioxide removal have grown on social media over the past decade. *Communications Earth & Environment*, **5**(763), 763. http://dx.doi.org/10.1038/s43247-024-01914-6

76) Abd Aziz, A., Nor Ghani, A., Sugiyama, M., del Barrio Alvarez, D., Cox, E., Spence, E. & Kamaludin, M. (2024). Public perception of Carbon Dioxide Removal (CDR) and its influencing factors: Evidence from a survey in Malaysia. *Sustainability Science.* http://dx.doi.org/10.1007/s11625-024-01587-2

75) Waller, L., Moats, D., Cox, E. & Bellamy, R. (2024) Questionable devices: applying a large language model to deliberate carbon removal. *Environmental Science & Policy*, **162**, 103940. http://dx.doi.org/10.1016/j.envsci.2024.103940

74) Holden, F.J., Davies, K., Bird, M.I., Hume, R., Green, H., Beerling D.J. & Nelson, P.N. (2024). In-field carbon dioxide removal via weathering of crushed basalt applied to acidic tropical agricultural soil. *Science of the Total Environment*. 955,176568. https://doi.org/10.1016/j.scitotenv.2024.176568

73) King, J. A., Weber, J., Lawrence, P., Roe, S., Swann, A. L. S. & Val Martin, M. (2024) Global and regional hydrological impacts of global forest expansion. *Biogeosciences*, 21, 3883–3902. https://doi.org/10.5194/bg-21-3883-2024

72) Cox, E., Bellamy, R. & Waller, L. (2024). Public attitudes and emotions toward novel carbon removal methods in alternative sociotechnical scenarios. *Environmental Research Letters* 19(8), article number: 84026. http://dx.doi.org/10.1088/1748-9326/ad5dd0

71) Epihov, D.Z., Banwart, S.A., McGrath, S.P., Martin, D., Kantola, I.B., Masters, M.D., DeLucia, E.H. & Beerling, D.J. (2024) Iron chelation in soil: a scalable biotechnology for accelerating carbon removal by

enhanced weathering of basalt. *Environmental Science & Technology* **58** (27), 11970-11987 https://doi.org/10.1021/acs.est.3c10146

70) Oppon, E., Lenny Koh, S.C. & Eufrasio, R. (2024) Sustainability performance of enhanced weathering across countries: A triple bottom line approach. *Energy Economics* **136**, 2024, 107722, https://doi.org/10.1016/j.eneco.2024.107722

69) Weber, J., Keeble, J., Abraham, N.L., Beerling, D.J. & Val Martin, M. (2024) Global agricultural N_2O emission reduction strategies deliver climate benefits with minimal impact on stratospheric O_3 recovery. *npj Climate and Atmospheric Science*, **7.** https://doi.org/10.1038/s41612-024-00678-2

68) Lamb, W.F., Müller-Hansen, F., Cox, E., Repke, T., Bellamy, R. & Lueck, S. (2024) Chapter 6: Public Perceptions and Communication. *The State of Carbon Dioxide Removal*, 2nd edition. https://www.stateofcdr.org/ https://doi.org/10.17605/OSF.IO/QN6FV

67) Cox, E., Shirani, F. & Rouse, P. (2024) Voices from the algorithm: Large language models in social research. *Energy Research and Social Science* 113. https://doi.org/10.1016/j.erss.2024.103559

66) Eufrasio Espinosa, R.M. & Lenny Koh, S.C. (2024) Forecasting the ecological footprint of G20 countries in the next 30 years. *Sci Rep* **14,** 8298. https://doi.org/10.1038/s41598-024-57994-z

65) Contzen, N., Perlaviciute,G., Steg, L., Reckels, S.C., Alves, S., Bidwell, B., Böhm, G., Bonaiuto, M., Chou, L-F., Corral-Verdugo, V., Dessi, F., Dietz, T., Doran, R., do Carmo Eulálio, M., Fielding, K., Gómez-Román, C., Granskaya, J.V., Gurikova, T., Hernández, B., Maira P., Kabakova, T., Lee, C-H., Li, F., Lima, M.L., Liu, L., Luís, S., Muinos, G., Ogunbode, C.A., Ortiz, M.V., Pidgeon, N., Argüello Pitt, M., Rahimi, L., Revokatova, A., Cecilia Reyna, C., Schuitema, G., Shwom, R., Yalcinkaya, N.S., Spence, E. & Sütterlin, B. (2024) Public opinion about solar radiation management: A cross-cultural study in 20 countries around the world. *Climatic Change* **177,** 65. https://doi.org/10.1007/s10584-024-03708-3

64) Hilser, H., Hiraldo, L., Moreau, C., Draiby, A., Cox., E., Andrews, M.G., Winks, L. & Walworth, N.G. (2024) Public engagement and collaboration for carbon dioxide removal: lessons from a project in the Dominican Republic. *Frontiers in Climate,* **6.** https://doi.org/10.3389/fclim.2024.1290999

63) Green, H., Larsen, P., Liu, Y. & Nelson, P.N. (2024) Carbon dioxide removal via weathering of sugarcane mill ash under different soil conditions. *Applied Geochemistry* 165, 105940. https://doi.org/10.1016/j.apgeochem.2024.105940

62) Weber, J., King, J. A., Abraham, L., Grosvenor, D., Smith, C., Shin, Y., Lawrence, P., Roe, S., Beerling, D.J. & Val Martin, M. (2024) Chemistry-albedo feedbacks offset up to a third of forestation's CO_2 removal benefits. *Science* **383,** 860-864. https://doi.org/10.1126/science.adg6196

[Perspective by Garry Hayman, Forestation is not an easy fix. *Science* **383,** 6685 (833-834) (2024). https://www.science.org/doi/10.1126/science.adn7026]

61) Beerling, D.J., Epihov, D.Z., Kantola, I.B., Masters, M.D., Reershemius, T., Planavsky, N.J., Reinhard, C.T., Jordan, J.S., Thorne, S.J., Weber, J., Martin, M.V., Freckleton, R.P., Hartley, S.E., James, R.H., Pearce, C.R., DeLucia, E.H. & Banwart, S.A. (2024) Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits. *Proceedings of the National Academy of Science of the United States of America* **121(9),** e2319436121. https://doi.org/10.1073/pnas.2319436121

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60) Hilser, H., Cox, E., Moreau, C., Hiraldo, L., Draiby, A., Winks, L., Andrews, M.G. & Walworth, N.G. (2024) Localized governance of carbon dioxide removal in small island developing states. *Environmental Development*, Volume 49, 2024,100942, https://doi.org/10.1016/j.envdev.2023.100942

59) Reershemius, T., Kelland, M.E., Jordan, J.S., Davis, I.R., D'Ascanio, R., Kalderon-Asael, B.K., Aseal, D., Surhhoff, T.J., Epihov, D.Z., Beerling, D.J., Reinhard, R.T. & Planavsky, N.J. (2023) Initial

validation of a soil-based mass-balance approach for empirical monitoring of enhanced rock weathering rates. *Environmental Science & Technology*, **57,** 19497-19507. https://doi.org/10.1021/acs.est.3c03609

58) Val Martin, M., Blanc-Betes, E., Fung, M.K., Kantzas, E.P., Kantola, I.B., Chiaravalloti, I., Taylor, L.L., Emmons, L.K., Wieder, W.R., Planavasky, N.J., Masters, M.D., DeLucia, M.D., Tai, A.P.K. & Beerling, D.J. (2023) Improved nitrogen cycle in a land surface model (CLM5) to quantity soil N_2O, NO, and NH_3 emissions from enhanced weathering with croplands. *Geoscientific Model Development*, **16,** 5783-5801. https://doi.org/10.5194/gmd-16-5783-2023

57) Renforth, P., Bellamy, R., Beerling, D., Boettcher, M., Bonalumi, Brandao, M., Fridahl, M., Fuss, S., Hansson, A., Heyward, C. Kolosz, B., Lamers, P., McLaren, D., Pomi, R., Sanchez, D.L., Shayegh, Sick, V., Van der Spek, M., Vishal, V. & Wilcox, J. (2023) Speciality grand challenge: renaming our section to 'Carbon Dioxide Removal'. *Frontiers in Climate*, **5,** https://doi.org/10.3389/fclim.2023.1279109.

56) Kantola, I. B., Blanc-Betes, E., Masters, M. D., Chang, E., Marklein, A., Moore, C. E., von Haden, A., Bernacchi, C. J., Wolf, A., Epihov, D. Z., Beerling, D.J. & DeLucia, E.H. (2023) Improved net carbon budgets in the US Midwest through direct measured impacts of enhanced weathering. *Global Change Biology*, 00, 1–17. https://doi.org/10.1111/gcb.16903

55) Oppon, E., Koh, S., Eufrasio, R. *et al.* (2023) Towards sustainable food production and climate change mitigation: an attributional life cycle assessment comparing industrial and basalt rock dust fertilisers. *Int J Life Cycle Assess* (2023). https://doi.org/10.1007/s11367-023-02196-4

54) Carr-Whitworth, R., Barrett, J., Colechin, M., Pidgeon, N., Style, R., Betts-Davies, S., Cox, E., Watson, A. & Wilson, O. (2023). Delivering net zero in the UK: Twelve conditions for success. *Environmental Research Letters* 18, 07404. http://dx.doi.org/10.1088/1748-9326/ace199

53) Beerling, D., Kantzas, E., Val Martin, M., Espinosa, R., Pidgeon, N. & Banwart, S. (2023) UK Government Policy Brief: Potential of enhanced rock weathering deployed with UK agriculture to sequester atmospheric carbon dioxide. Available at *figshare. Online resource*. https://doi.org/10.6084/m9.figshare.22888646.v3

52) West, L.J., Banwart, S.A., Val Martin, M., Kantzas, E. & Beerling, D.J. (2023) Making mistakes in estimating the CO_2 sequestration potential of UK croplands with enhanced weathering. *Applied Geochemistry*, **151,** 105591, https://doi.org/10.1016/j.apgeochem.2023.105591

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51) Larkin, C.S., Andrews, M.G., Pearce, C.R., Yeong, K.L., Beerling, D.J., Bellamy, J., Benedick, S., Freckleton, R.P., Goring-Harford, H., Sadekar, S. & James, R.H. (2022) Quantification of CO_2 removal in a large-scale enhanced weathering field trial on an oil palm plantation in Sabah Malaysia. *Frontiers Climate*, **4,** https://doi.org/10.3389/fclim.2022.959229.

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48) Vienne, A., Poblador, S., Portillo-Estrada, M., Hartmann, J., Ijiehon, S., Wade, P. & Vicca, S. (2022) Enhanced Weathering Using Basalt Rock Powder: Carbon Sequestration, Co-benefits and Risks in a Mesocosm Study With Solanum tuberosum. *Front. Clim.* 4:869456. https://doi.org/10.3389/fclim.2022.869456

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46) Cox, E., Spence, E. & Pidgeon, N. (2022) Deliberating enhanced weathering: Public frames, iconic ecosystems and the governance of carbon removal at scale. *Public Understanding of Science*. doi:10.1177/09636625221112190

45) Semieniuk, G., Holden, P.B., Mercure, J-F, Salas, P., Pollitt, H., Jobson, K., Vercoulen, P., Chewpreecha, U., Edwards, N.R. & Vinuales, J.E. (2022) Stranded fossil-fuel assets translate to major losses for investors in advanced economies. *Nature Climate Change*, **12**, https://doi.org/10.1038/s41558-022-01356-y.

44) Eufrasio, R.M., Kantzas, E.P., Edwards, N.R., Holden, P.B., Pollitt, H., Mercure, J.F., Koh, S.C.L. & Beerling, D.J. (2022) Environmental and health impacts of atmospheric CO_2 removal by enhanced rock weathering depend on nations' energy mix. *Communications Earth & Environment*, **3**, 106. https://doi.org/10.1038/s43247-022-00436-3

43) Kantzas, E.P., Val Martin, M., Lomas, M.R., Eufrasio, R.M., Renforth, P., Lewis, A.L., Taylor, L.L., Mercure, J.F., Pollitt, H., Vercoulen, P.V., Vakilifard, N., Holden, P.B., Edwards, N.R., Koh, L., Pidgeon, N.F., Banwart, S.A. & Beerling, D.J. (2022) Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nature Geoscience*, **15**, 382-389. https://doi.org/10.1038/s41561-022-00925-2

[Commentary on #43: *Nature Geoscience*, **15,** 341, 2022]

This paper reports the first coupled dynamic enhanced rock weathering model findings in which a soil profile weathering model is coupled to a land surface model with nitrogen cycle representation. The modelling advance is akin to moving from equilibrium vegetation models developed in the 1980s to dynamic global vegetation models now embedded in Earth system models. It allows us to account mechanistically for N-fertilizer effects on basal mineral weathering rates. Simulations are uniquely (for ERW modelling analyses) constrained by resource production scenarios. We to show adding rock dust to UK agricultural soils could remove between 6 and 30 million tonnes of carbon dioxide (CO_2) from the atmosphere annually by 2050 -- up to 45 per cent of the atmospheric carbon dioxide removal needed for the UK to reach net zero.

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39) James, R., Bullock, L., Larkin, C. & Matter, J. (2021) Geological solutions for carbon dioxide removal. *Geoscientist* (autumn), 16-22.

38) Vakilifard, N., Kantzas, E.P., Edwards, N.R., Holden, P.B. & Beerling, D.J. (2021) The role of enhanced weathering deployment with agriculture in limiting future warming and protecting coral reefs. *Environmental Research Letters*, **19,** 094005. https://doi.org/10.1088/1748-9326/ac1818

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capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry*, **132,** 105023. https://doi.org/10.1016/j.apgeochem.2021.105023

35) Spence, E., Cox, E. & Pidgeon, N. (2021) Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. *Climatic Change*, **165**, art. 23 https://doi.org/10.1007/s10584-021-03050-y

34) Horton, P., Long, S.P., Smith, P., Banwart, S.A. & Beerling, D.J. (2021) Technologies to deliver food and climate security through agriculture. *Nature Plants*, **7**, 250–255. https://doi.org/10.1038/s41477-021-00877-2

33) Epihov, D.Z., Saltonstall, K., Batterman, S.A., Hedin, L.O., Hall, J.S., van Breugel, M., Leake, J.R. & Beerling, D.J. (2021) Legume-microbiome interactions unlock mineral nutrients in regrowing tropical forests. *Proceedings of the National Academy of Sciences, USA,* **118,** e2022241118. https://doi.org/10.1073/pnas.2022241118.

Paper #33 reports enhanced weathering by N_2-fixing legumes trees in tropical forests facilitated by the recruitment of a below-ground microbiome that also benefits neighbouring trees.

32) Cox, E., Spence, E. & Pidgeon, N. (2021) But They told us it was safe! Carbon dioxide removal, fracking, and ripple effects in risk perceptions. *Risk Analysis*. https://doi.org/10.1111/risa.13717.

31) Cox E., Spence, E. & Pidgeon, N. (2021) What people think about Carbon Dioxide Removal. Leverhulme Centre for Climate Change Mitigation, University of Sheffield, U.K. [White Paper] Available at http://lc3m.org/publications/

30) Cox, E., Boettcher, M., Spence, E. & Bellamy, R. (2021) Casting a wider net on ocean NETs. *Frontiers in Climate*. https://doi.org/10.3389/fclim.2021.576294.

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28) Blanc-Betes, E., Kantola, I.B., Gomez-Casanovas, N., Hartman, M.D., Parton, W.J., Lewis, A.L., Beerling, D.J. & DeLucia, E.H. (2020) In silico assessment of the potential of basalt amendments to reduce N_2O emissions from bioenergy crops. *GCB Bioenergy*, **13**, 224-241. http://dx.doi.org/10.1111/gcbb.12757

Paper #28 reports first evidence from LC^{3}M field trials for consistent mitigation of N_2O fluxes from US corn-belt soils over three growing seasons following basalt amendment.

27) Beerling, D.J., Kantzas, E., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Quirk, J., Sarkar, B., Andrews, G., James, R.H., Pearce, C.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I., Hansen, J. & Banwart, S.A. (2020) Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. *Nature*, **583**, 242-248. https://doi.org/10.1038/s41586-020-2448-9

[Commentary on #26: News & Views, *Nature*, **583,** 204-205; Editorial, *Nature*, **583,** 167-168, 2020]

Paper #24 develops the theory to simulate the weathering of particle size distributions, and an initial nation-by-nation assessment of CO_2 removal potential by enhanced weathering constrained by current and future energy policy scenarios using an advanced and robust computationally efficient modelling approach.

26) Cox, E., Spence, E. & Pidgeon, N. (2020) Public perceptions of carbon dioxide removal in the United States and the United Kingdom. *Nature Climate Change,* **10**, 744-749. https://doi.org/10.1038/s41558-020-0823-z

25) MacDougall, A.H., Frölicher, T.L., Jones, C.D., Rogelj, J., Matthews, H.D., Zickfeld, K., Arora, V.K., Barrett, N.J., Brovkin, V., Burger, F.A., Eby, M., Eliseev, A.V., Hajima, T., Holden, P.B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I.I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra, J., Wiltshire, A. & Ziehn, T. (2020) Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences*, **17**, 2987–3016. https://doi.org/10.5194/bg-17-2987-2020

24) Kelland, M.E., Wade, P.W., Lewis, A.L., Taylor, L.L., Sarkar, B., Andrews, M.G., Lomas, M.R., Cotton, T.E.A., Kemp, S.J., James, R.H., Pearce, C.R., Hartley, S.E., Hodson, M.E., Leake, J.R., Banwart, S.A. & Beerling, D.J. (2020) Increased yield and CO_2 sequestration potential with the C_4 cereal *Sorghum bicolor* cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*, **26**, 3658–3676. https://doi.org/10.1111/gcb

Paper #24 reports the first evidence from mesocosm experiments that amendment of a UK agricultural soil with crushed basalt increased yields of the C_4 crop Sorhum and introduced a detailed 1-D soil profile PhreeqC reactive transport model for simulating rock grain weathering and carbon capture.

23) Pidgeon, N. (2021) Engaging publics about environmental and technology risks: frames, values and deliberation. *Journal of Risk Research*, **24**, 28-46. https://doi.org/10.1080/13669877.2020.174911

22) Cox, E., Spence, E. & Pidgeon, N. (2020) Incumbency, trust, and the Monsanto effect: stakeholder discourses on greenhouse gas removal. *Environmental Values*, **29**, 197-220. https://doi.org/10.3197/096327119X15678473650947

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21) Lawrence, D. M. et al (including Val Martin, M). (2019) The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems*, **11,** 4245-4287. https://doi.org/10.1029/2018MS001583

20) Cox, E., Royston, S. & Selby, J. (2019) From exports to exercise: how non-energy policies affect energy systems. *Energy Research and Social Science*, **55**, 179-188. https://doi.org/10.1016/j.erss.2019.05.016

19) Beerling, D.J. (2019) Can plants help us avoid seeding a human-made climate catastrophe? *Plants, People, Planet.* **1,** 310-314. https://doi.org/10.1002/ppp3.10066

18) Andrews, M.G. & Taylor, L.L. (2019) Combating climate change through enhanced weathering of agricultural soils. *Elements,* **15**, 253-258. https://doi.org/10.2138/gselements.15.4.253

17) Cox, E. & Edwards, N.R. (2019) Beyond carbon pricing: policy levers for negative emissions technologies. *Climate Policy*, **19**, 1144-1156. https://doi.org/10.1080/14693062.2019.1634509

16) Smith, P., Adams, J., Beerling, D.J., Beringer, T., Calvin, K.V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J.C., Popp, A., Renforth, P., Vicente-Vicente, J.L. & Keesstra, S. (2019) Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. *Annual Review of Environment and Resources,* **44,** 255-286. https://doi.org/10.1146/annurev-environ-101718-033129

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15) Arnold, S.R., Lombardozzi, D., J-F Lamarque, T. Richardson, L.K. Emmons, S. Tilmes, S.A. Sitch, G. Folberth, M.J. Hollaway, M. Val Martin (2018) Simulated global climate response to tropospheric ozone-induced changes in plant transpiration, *Geophysical Research Letters*, **45.** https://doi.org/10.1029/2018GL079938

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[Commentary on #9: Editorial *Nature* **554**, 404-405, 2018]

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