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Perspective

Operationalizing marketable blue carbon

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SUMMARY

The global carbon sequestration and avoided emissions potentially achieved via blue carbon is high (∼3% of annual global greenhouse gas emissions); however, it is limited by multidisciplinary and interacting uncertainties spanning the social, governance, financial, and technological dimensions. We compiled a transdisciplinary team of experts to elucidate these challenges and identify a way forward. Key actions to enhance blue carbon as a natural climate solution include improving policy and legal arrangements to ensure equitable sharing of benefits; improving stewardship by incorporating indigenous knowledge and values; clarifying property rights; improving financial approaches and accounting tools to incorporate co-benefits; developing technological solutions for measuring blue carbon sequestration at low cost; and resolving knowledge gaps regarding blue carbon cycles. Implementing these actions and operationalizing blue carbon will achieve measurable changes to atmospheric greenhouse gas concentrations, provide multiple co-benefits, and address national obligations associated with international agreements.

INTRODUCTION

The effects of rising carbon dioxide levels in the atmosphere are compromising our oceans by changing species productivity, distribution and abundance through ocean warming, acidification, deoxygenation, and sea-level rise.[1] The altered ecosystem structure and functioning associated with these climatic pressures are exacerbated by further anthropogenic activities, such as nutrient enrichment and fishing.[1] Human communities are very dependent on the ocean through the goods and services they provide, and the changes occurring in the oceans will have consequences for their wellbeing.[2] Thus, a sustainable society requires a stabilized climate and retention of biodiversity to provide healthy ecosystems.[1] In restoring ocean health, the most urgent requirement has been identified as tackling climate change, as this is the primary cause of ocean change.[3]

Several strategies are being pursued to mitigate the climate emergency and keep global temperature increase below 1.5°C by the end of this century. While all pathways require rapid and substantial decarbonization alongside other transitions in the energy, transport, and building sectors, it is being increasingly recognized that ''natural climate solutions'' (NCS) are an essential component of any strategy.[4] NCS encompass a range of habitat-management interventions that reduce emissions or sequester additional atmospheric carbon dioxide and have been estimated to be capable of removing 23.8 Pg of carbon from the atmosphere per year.[5]

Blue carbon refers to carbon that is captured and stored by coastal and marine ecosystems, and a widely accepted definition includes all fluxes and stores that are biologically driven and are responsive to management.[1] While multiple ocean and coastal ecosystems sequester and store significant amounts of carbon, there is still a debate regarding the inclusion of some ecosystems in the blue carbon framework.[6,7] Particular attention has been focused on vegetated coastal ecosystems such as mangroves, saltmarshes, and seagrasses due to their high carbon storage and long-term sequestration capacity compared with terrestrial forest ecosystems, making them among the Earth's most efficient long-term carbon sinks.[8–12] The scientific understanding of stocks and greenhouse gas fluxes has meant that these ecosystems have already been recognized for their climate-mitigation potential and are now included in international policies such as the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas accounting methodologies.[13] These vegetated coastal ecosystems—or ''blue carbon ecosystems''—also protect coasts from erosion and extreme weather (including flooding), bolster fisheries, support unique biodiversity, improve water quality by filtering nutrients and pollutants, and contribute to growing aquaculture and eco-tourism sectors.[8,14] Yet, their areal extent has declined globally, mainly due to land-use change and over-exploitation,[15] with profound impacts on the Earth's climate by releasing stored blue carbon into the atmosphere,[16] and diminished contributions to biodiversity, coastal resilience, and local communities.

The potential supply of blue carbon is large, with large-scale protection and restoration of mangroves, tidal marshes, and seagrasses capable of removing ∼3% of annual global greenhouse gas emissions.[17] For example, 20% of the world's mangrove forests may qualify for carbon-credit schemes, and 10% may be profitable, potentially generating US $1.2 billion per year in carbon benefits.[18] Matching this potential supply, there is rapidly increasing demand from industry and government interest in the potential of protecting and restoring blue carbon ecosystems as an NCS. Several major international corporations—such as Apple, HSBC, and BHP—have announced their intentions to include blue carbon within their carbon-abatement portfolio, while some countries (e.g., Australia, USA, and UAE) have already incorporated blue carbon into their nationally determined contributions under the Paris Agreement.[19]

Despite high global enthusiasm for blue carbon as an NCS, conservation and restoration of blue carbon ecosystems employing carbon-based mechanisms in NCS has not dramatically increased.[20] Converting commitments by governments, the private sector, and others into tangible outcomes is hindered by uncertainties (challenges) that currently limit blue carbon from being realized as a viable NCS. The major sources of uncertainty span social, governance, finance, technical, and scientific dimensions yet remain difficult to resolve as they are both multidisciplinary and interacting. To address this problem, we compiled a transdisciplinary team of economists, policy specialists, engineers, social scientists, ecologists, decision scientists, mathematicians, biogeochemists, geomorphologists, and carbon-market specialists to identify major sources of uncertainty in operationalizing marketable blue carbon as an NCS, propose a way forward that addresses uncertainties, and recommend priority research and management actions to reduce or ameliorate these uncertainties. In doing so, we encourage blue carbon projects that are highly beneficial to the natural environment and to society in a way that is scalable, replicable, and cost effective.

MAJOR SOURCES OF UNCERTAINTY

Examination of past restoration and conservation projects linked to carbon-credit markets including terrestrial carbon offset programs, illustrate that there are key social challenges to the delivery of the diverse activities required for transformation. Challenges include a lack of knowledge about how proposed activities align with community values, behaviors, and perceptions of risk, what individual and collective capacities are required to facilitate sustainable change, and the role of local and indigenous knowledge in blue carbon projects.[21–23] Blue carbon projects present unique challenges of access and logistics relative to those in terrestrial systems;[24] there are also additional concerns where benefits are unevenly distributed or whether particular activities reinforce and/or exacerbate social inequity[25,26] or where incentives and benefits are not sufficient to attract, harness, and maintain broad community participation.[27] Blue carbon projects should be designed with the objective of achieving multiple benefits that meet current and future needs[28] and benefit current and future users; indeed, this may be the key to success in terms of effective long-term participation and ecosystem management.[29]

From a governance perspective, coastal vegetated ecosystems occupy intertidal and subtidal zones, which are often contested spaces from a legal perspective; for example, mangroves often straddle the boundary between privately owned and state-owned land, and seagrasses and seaweeds can exist beyond exclusive economic zones or within countries where state and national laws conflict. Consequently, in some countries, there is confusion related to land tenure and how it intersects with the blue carbon market,[28] such as who ''owns'' the blue carbon and who has the right to transact carbon credits for a given blue carbon project: the landholder, the project developer, Indigenous groups, or the national/sub-national government? For example, rights to carbon credits for REDD+ projects in Indonesia have been contested because land ownership does not always give rights to the carbon.[30] Similarly, governments apply different rules for demarcating the boundary between public and private land, and these boundaries may not be easily determined in circumstances where human modifications to the coastal zone such as floodgates, levees, and dykes have affected tidal boundaries.[31] Transboundary issues may become even more challenging for seaweed carbon or alkaline (carbonate and bicarbonate) flows, where the carbon sink is spatially removed from the coastal vegetation source.[32] Furthermore, existing legal frameworks rarely consider how management activities may affect the response of coastal wetlands to sea-level rise and other climate-change factors. Planning for landward retreat of coastal wetlands with sea-level rise and managing permanence and land tenure as this occurs is complex, and novel legal issues arise.[33,34] In Australia, tenure issues have been overcome to some extent through contractual agreements whereby parties agree where carbon ownership lies irrespective of underlying property-based rights.[35]

These social and governance uncertainties are compounded by the need for global climate finance to increase from the current investment of US $608–622 billion to US $1.6–3.8 trillion in order to keep warming within a 1.5°C scenario.[36] The coronavirus 2019 (COVID-19) pandemic and concomitant socio-economic crisis will ostensibly make this task more challenging, but there is an opportunity to implement recovery stimulus plans that reallocate finance toward "natural capital" investments—including blue carbon. The World Economic Forum estimates that a US $2.7 trillion investment to transition several of our socio-economic systems to "nature-positive" pathways could return US $10.1 trillion in economic growth and 395 million jobs by 2030.[37] Blue carbon is attracting much interest from investors, and there is a growing pipeline of blue carbon projects globally, but overall the pipeline of blue carbon projects occurring on the ground is often constrained by lack of certainty on the risk-return ratio, implementation pathway, and policy/legislation. Consequently, this has created a situation where demand for investible blue carbon projects is outweighing supply. This dilemma is also seen with other types of NCS that are nascent; currently NCS receive only 3% of global climate finance, yet they could be responsible for achieving a third of all emissions reduction needed to keep global warming under 2°C by 2030.[5]

Supply of projects and willingness of governments to develop blue carbon policy may be ameliorated if there was greater certainty in carbon-sequestration opportunities, a challenge that can be improved with technical solutions and associated capacity building. There is need to improve our ability to parameterize sequestration from blue carbon ecosystems accurately, and cost effectively, with standardized methods, particularly during restoration and in response to climate change and other disturbances. We need to explore relatively unknown physico-chemical pathways within the blue carbon cycle that could be globally significant, such as carbonate production and dissolution, alkalinity (carbonate and bicarbonate in seawater) export, and the contribution of seaweed carbon to deeper ocean sinks.[7] IPCC Tier 1 values (i.e., globally-averaged values used by any country that does not have country-level values) for blue carbon drawdown (avoided emissions and sequestration) exist for a range of activities for mangroves, seagrass and tidal marshes,[13] but Tier 2 (nationally relevant country-level values) and 3 (models) approaches are few. Knowledge of methane and nitrous oxide emissions from degraded landscapes, and their reduction with rehabilitation of coastal ecosystems, could add substantially to the value of blue carbon projects; yet, these data are only recently emerging and require further assessment.[13,38] To decrease uncertainty in estimates of blue carbon storage and sequestration, we need to parameterize carbon and greenhouse gas benefits of ecosystem protection and rehabilitation and its variation with environmental conditions over space and time, including with sea-level rise and other impacts of climate change.

THE WAY FORWARD: RESOLVING UNCERTAINTIES

To address these uncertainties, the first step is transforming the research and management landscape (Figure 1). For truly transformative change, seeking and incorporating social-equity solutions and opportunities and appropriate management systems for traditional knowledge must be considered alongside environmental and economic concerns.[28] Injustices are already being perpetuated by growth in the blue economy,[26] and there is active and timely debate about reform; however, how to apply and integrate Indigenous and local knowledge in blue carbon mitigation remains a key gap.[21,22] We underscore calls for more concerted efforts to finds ways of working across diverse knowledge systems for future environmental goals.[39] Fortunately, there are excellent opportunities to align blue carbon-credit incentives with other benefits, such as sustainable eco-tourism ventures, enhancing fisheries habitat, water quality, and coastal protection, as well as key lessons to be learned from coastal- and marine-protected area management in terms of what underpins local and long-term support.[22] Research attention to the social dimensions of blue carbon activities and meeting the diverse needs of private- and public-sector goals and interests is therefore critical for successful adoption, longevity, and ongoing social legitimacy.

While contractual agreements may be appropriate in some instances, clarifying land and carbon ownership and governance arrangements is critical to establishing who holds the legal rights to generate carbon credits from a project area now and in the future. This is particularly important for lands with complex land tenures (e.g., multiple stakeholders including farmers, lease holders, various levels of government, and traditional owners) or where blue carbon projects have been explicitly designed to achieve multiple benefits that must be shared among multiple stakeholders (e.g., in the case of stacking environmental credit markets). Furthermore, financial viability is often enhanced with project size, which necessitates working with multiple land and carbon owners, thereby increasing the transaction costs associated with project establishment, and requiring novel solutions that might include mechanisms like common-asset trusts.[40]

A broad range of finance approaches are needed to underpin proposed advances in social and governance uncertainties; these approaches span public funding (e.g., environmental levies, covenanted tax deductions, debt-for-nature swaps), philanthropy (e.g., corporate social responsibility, corporate-cause marketing programs), and private investment (e.g., blue bonds), as well as the potential for innovative economic accounting tools (e.g., blockchain) to reduce transaction costs. There are good examples of where these aforementioned approaches have been tested for other forms of conservation finance (e.g., for terrestrial ecosystems), providing a rich knowledge base to learn from and trial in a blue carbon context.[36,41–43] For blue carbon to meaningfully contribute to keeping warming within a 1.5°C scenario, there is a global need for the development and evaluation

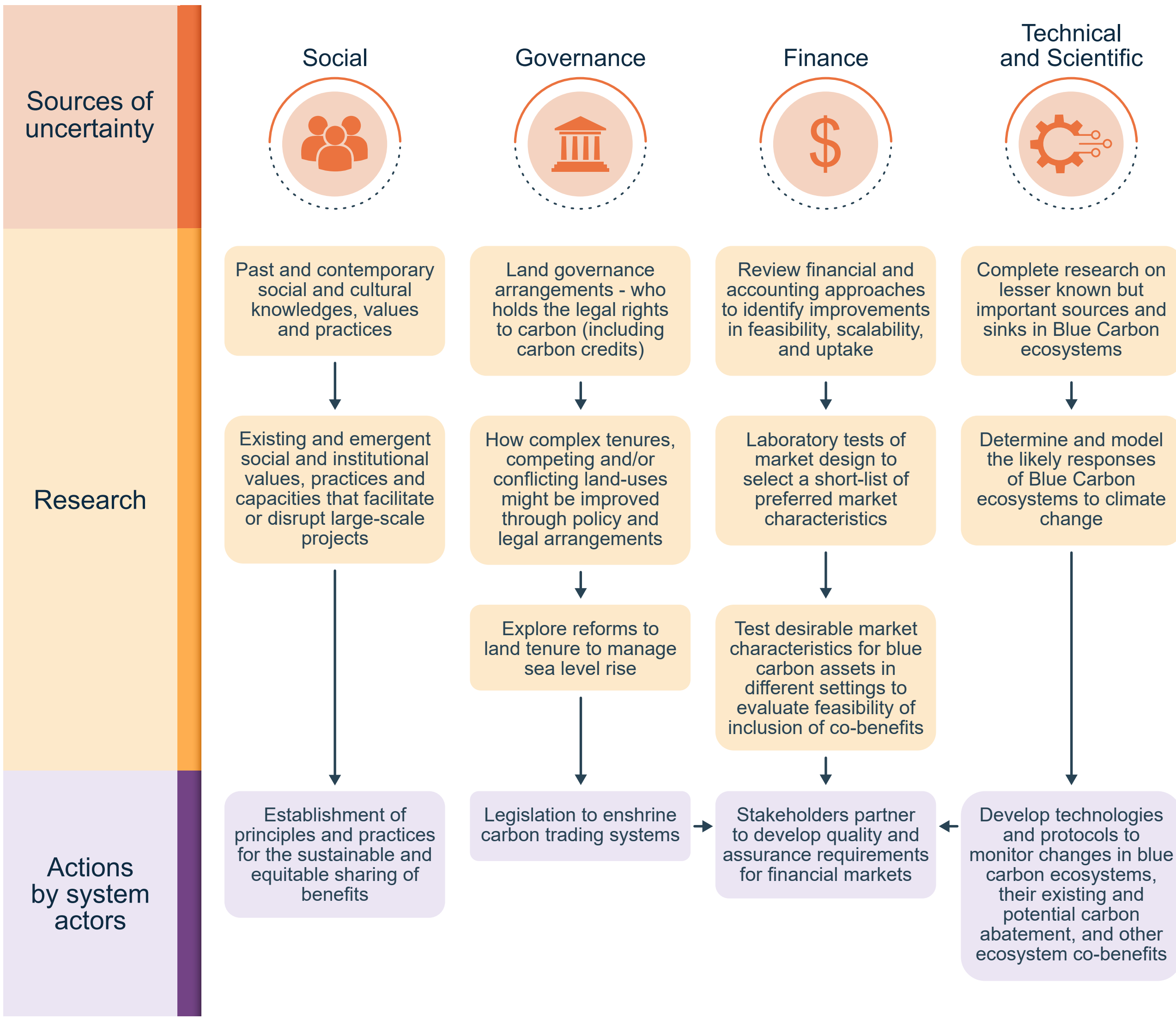

Figure 1. Framework for operationalizing marketable blue carbon
Research and implementation priorities for the four main sources of uncertainty in blue carbon projects are shown. Arrows indicate important dependencies.

of self-sustaining strategies for financing blue carbon. Though there are some exceptions—and the economics are highly dependent on the local context of the project—blue carbon projects can involve high up-front project costs and relatively expensive measurement and verification methods. As such, particularly in developed economies, blue carbon projects may not be financially viable on carbon crediting alone in the short-to-medium term, even with forecasted credit price increases and increasing demand for carbon credits to meet voluntary targets and compliance requirements.[43] Thus, the key to financing blue carbon projects at scale will be to bundle and stack carbon-credit revenue with other sources of revenue.[44]

Much attention has focused on carbon markets as an obvious choice for financing blue carbon projects, but given the numerous co-benefits (e.g., nutrient removal,[45] fisheries enhancement,[46] and coastal protection),[47,48] there is potential to boost investments by combining blue carbon credits with other environmental credits. This could be through products, such as seaweed products,[49] or through finding mechanisms to properly value the co-benefits provided by blue carbon projects and buyers to pay for them. Payment for these co-benefits could occur through premium prices for "carbon + co-benefits" credits, through the layering of government and philanthropic funds, or through direct payments from those who benefit from blue carbon projects such as insurers and tourism and aquaculture operators.[50] Robust metrics and verification tools will be required to support claims for co-benefits, which is challenging for aspects such as biodiversity, that are not easily quantifiable or fungible and comparable between projects and settings. While the market for carbon credits is well established, the market of biodiversity and nature credits is now beginning to emerge. A leading verification standards body is promoting a climate, community, and biodiversity standard that transparently assesses the contribution of a carbon-credit project to a range of

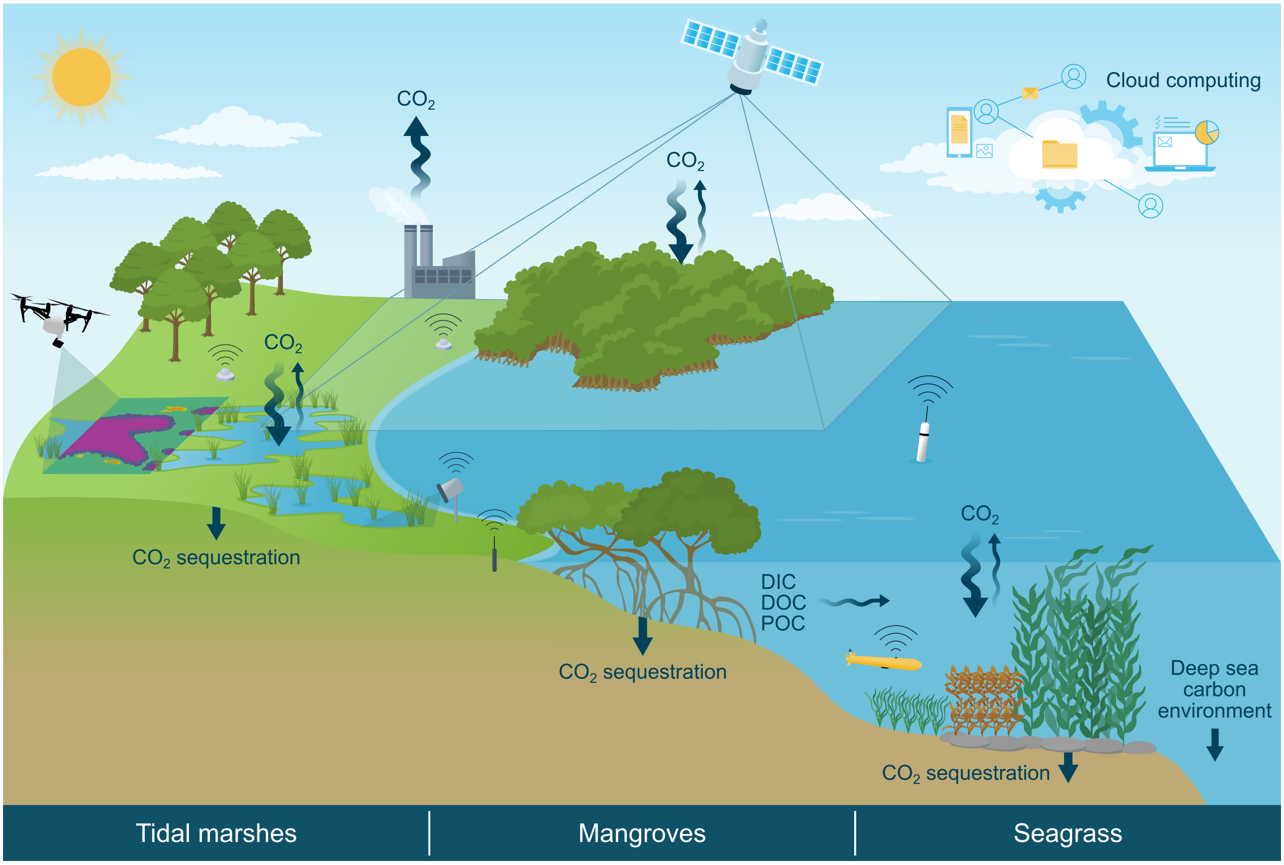

Figure 2. Advanced observation technology and analytical tools to improve the parameterization of blue carbon
Includes developing robust low-cost sensors that facilitate monitoring and verification of blue carbon drawdown. For example, data from hyperspectral, multispectral, Lidar, and radar sensors on airborne and/or unmanned aerial vehicle (UAV)-derived (indicated on the left of the image) and those from satellites (central in the image) could be integrated, refined, and validated with artificial-intelligence tools and robust models using cloud computing (right of image) that integrate disparate data to develop and verify blue carbon-project outcomes and characterize the value of other ecosystem services that benefit coastal communities and their sustainability, such as coastal protection, fisheries' productivity, and biodiversity. Seagrass ecosystems are depicted co-occuring with seaweed forests, which are potential blue carbon ecosystems that are not currenlty included in traditional frameworks.

key biodiversity and livelihood criteria. Currently, almost 200 projects have been assessed against these criteria.[51] Project developers are also beginning to promote the quantification of biodiversity as a marketable credit option.[52]

These quality-assurance requirements will be partly met with technical solutions, and it is now time for developing and applying advanced observation technology and analytical tools to improve the parametrization of blue carbon drawdown, including measuring, tracking, and modeling spatial and temporal changes in blue carbon ecosystems and their carbon-sink capacity at low cost, using standardized methods that can be widely implemented (Figure 2). Further investment in scientific and technical capacity will aid opportunities to investigate blue carbon drawdown through additional, lesser-known pathways. For example, the export of alkalinity from mangroves to oceans,[53] the export of dissolved and particulate carbon from seagrass and seaweed to the deep oceans,[54] and the role of carbonates[55] could be important carbon-capture mechanisms arising from blue carbon ecosystems. Although these pathways are not included in IPCC estimates of greenhouse gas emissions[13,] or blue carbon methodologies,[56] it is anticipated that these processes could be incorporated into future national greenhouse gas inventories when future research provides the necessary evidence for specific management activities that also inlude data on the complete blue carbon cycle.[32] For example, DNA tracing of exported carbon in marine sediments and water samples[57] and recent high-resolution shelf-scale current models, e.g., Liu et al.,[58] can be used to assess exports of seaweed (“allochthonous” blue carbon) from coastal habitats to deep ocean sinks.

Integration of these actions into a true transdisciplinary research, development, and extension program will be the key to success in delivering an operational market for blue carbon that includes co-benefits and provides attractive investment opportunities at an appropriate scale. We suggest that agreement on the principles and practices for sustainable and equitable benefits provides the overarching value proposition and vision for those involved in blue carbon programs.[59] Legislation to enshrine carbon-trading systems and the development of technologies and protocols to monitor all co-benefits of blue carbon systems will together create the quality and assurance required to develop attractive financial arrangements for a range of investors (Figure 1). A series of poorly connected research projects will not provide a timely solution to the challenges, and success will depend on (1) arrangements for diverse, non-research stakeholders to input priorities and to shape solutions and (2) joint-venture research arrangements with clear governance and leadership to promote (3) continual opportunities for cross-discipline objective settings and the integration of research findings.

PRIORITY ACTIONS

The development requirements for blue carbon projects will vary in different situations. However, achieving a step change in the number and scale of future blue carbon programs will depend on a priority set of research actions and management outcomes. These include the following:

- Understanding past and contemporary social and cultural knowledges, values, and practices and how they can improve stewardship of blue carbon ecosystems.
- Determining existing and emergent social and institutional values, norms, practices, and capacities that facilitate or disrupt large-scale restoration and protection of blue carbon ecosystems.
- Clarifying land and governance arrangements and carbon ownership will establish who holds the legal rights to carbon accumulated (including carbon credits) for current and future blue carbon projects. Where uncertainty pervades, rights to carbon can be established and secured contractually.
- Investigating and developing solutions for land tenure for coastlines where sea-level rise is anticipated to change the distribution of blue carbon assets, such as "rolling covenants" that balance short-term use of land with inland wetland migration.[60] Issues related to land ownership become more complex when the project-area boundary is shifting. In addition, shifting boundaries add uncertainty to carbon accounting, such as cases where forest carbon stocks are converting to marsh carbon stocks[61] or vice versa.[62,63]
- Providing evidence-informed guidance on how complex tenures and competing and/or conflicting land-use practices might be responded to and be improved through policy and legal arrangements. For example, clarity may be required in cases where the land-use rights of a property do not clearly convey the right to sell carbon or when legal frameworks are in conflict with the traditional and customary claims of the local population.
- Evaluating the range of financial approaches and economic accounting tools that are suitable for blue carbon projects to identify possible improvements in terms of their financial and practical feasibility, scalability, and uptake. This will likely involve combining different tools to bridge the funding gap between income generated from carbon credits versus project establishment, maintenance, and monitoring costs.
- Designing and testing market characteristics for blue carbon assets in different countries inclusive of co-benefits such as coastal protection, tourism and recreation, and biodiversity and fisheries enhancement. This will allow the stacking of multiple ecosystem service credits and has already begun to be conceptualized through "resilience credits," where buyers pay for both carbon and coastal protection.
- Addressing arrangements that will bridge the current major gap between investors and possible project implementation. This will involve blue carbon researchers, communities, the financial sector, and government creating key quality and assurance requirements to underpin blue carbon projects. Encouraging partnerships are beginning to emerge that bring together at least some of these stakeholder groups, such as the Blue Carbon Buyers Alliance and the Blue Carbon Accelerator Fund.
- Closing knowledge gaps on sources and sinks in blue carbon cycles such as the export of alkalinity to the coastal oceans, the contribution of seaweed to blue carbon, the role of carbonates, and the measurement of methane and nitrous oxide that are required to identify credible greenhouse gas offset benefits.
- Exploring options for blue carbon action beyond vegetated coastal ecosystems, including managing sediments within continental shelf areas to avoid potentially large[64] emissions from disturbance, such as trawling, determining the benefits of marine-protected areas for climate-change mitigation,[65] as well as those from changes in the management of fish catches, and other possible actionable options to increase the role of healthy marine ecosystems in sequestering carbon.[66]
- Developing efficient, cost-effective technologies and standardized protocols to monitor changes in blue carbon ecosystem distribution, their existing and potential carbon abatement, and other ecosystem co-benefits.
- Reducing uncertainty in how blue carbon ecosystems and their carbon storage/accumulation capacity will respond to climate change and other disturbances and developing technical solutions to reduce risks.

CONCLUSIONS

We propose a priority set of cross-cutting actions to optimize blue carbon as an NCS. A linked and integrated research program scaled to circumstances can overcome uncertainties that are current barriers to the widespread implementation of blue carbon projects for NCS. Understanding the values, ownership, and governance of wetland resources sets an agreed societal framework for investment in blue carbon projects and informs the ethical and legal frameworks required to benefit owners and investors. Linked research on the economic value of resources and the financial products required to attract the scale of funding required to optimize blue carbon projects will also be informed by scientific knowledge that reduces uncertainties in carbon estimates, ecosystem restoration, and remote assessment of carbon and greenhouse gas to minimize costs. Combining social, economic, and technical understandings will reinforce the trust in and quality assurance for financial products. Critically, the actions we propose will help establish blue carbon as much more than an NCS and will deliver broader outcomes in sustainable development of resources and wetland and biodiversity conservation, all of which will add value to financial products. Such a research program will involve a range of blue carbon "actors" spanning

Indigenous people, scientists, policy makers and practitioners, technology developers, carbon-methodology experts, governments, project developers, the finance sector, industry, nongovernmental organizations (NGOs), and philanthropy.

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AUTHOR CONTRIBUTIONS

All authors contributed to the writing and editing of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing financial interests.

REFERENCES

1. Intergovernmental Panel on Climate Change (IPCC). (2022). Changing Ocean, Marine Ecosystems, and Dependent Communities. In The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press), pp. 447–588.
2. Scholes, R., Hassan, R., and Ash, N.J. (2005). Ecosystem and human well-being: current state and trends. In The Millennium Ecosystem Assessment Series, *1* (Island Press), pp. 1–23.
3. Laffoley, D., Baxter, J.M., Amon, D.J., Currie, D.E.J., Downs, C.A., Hall-Spencer, J.M., Harden-Davies, H., Page, R., Reid, C.P., Roberts, C.M., et al. (2020). Eight urgent, fundamental and simultaneous steps needed to restore ocean health, and the consequences for humanity and the planet of inaction or delay. Aquat. Conserv. Mar. Freshw. Ecosyst. *30*, 194–208. https://doi.org/10.1002/aqc.3182.
4. Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In 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, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, and R. Pidcock, et al., eds. (Intergovernmental Panel on Climate Change), pp. 93–174.
5. Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., et al. (2017). Natural climate solutions. Proc. Natl. Acad. Sci. U.S.A. *114*, 11645–11650. https://doi.org/10.1073/pnas.1710465114.
6. Lovelock, C.E., and Duarte, C.M. (2019). Dimensions of blue carbon and emerging perspectives. Biol. Lett. *15*, 20180781. https://doi.org/10.1098/rsbl.2018.0781.
7. Macreadie, P.I., Anton, A., Raven, J.A., Beaumont, N., Connolly, R.M., Friess, D.A., Kelleway, J.J., Kennedy, H., Kuwae, T., Lavery, P.S., et al. (2019). The future of Blue Carbon science. Nat. Commun. *10*, 3998. https://doi.org/10.1038/s41467-019-11693-w.
8. McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Bjork, M., Duarte, C.M., et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front. Ecol. Envir. *9*, 552–560. https://doi.org/10.1890/110004.
9. Ouyang, X., and Lee, S.Y. (2014). Updated estimates of carbon accumulation rates in coastal marsh sediments. Biogeosciences *11*, 5057–5071. https://doi.org/10.5194/bg-11-5057-2014.
10. Alongi, D.M. (2012). Carbon sequestration in mangrove forests. Carbon Management *3*, 313–322. https://doi.org/10.4155/cmt.12.20.
11. Serrano, O., Lovelock, C.E., B Atwood, T., Macreadie, P.I., Canto, R., Phinn, S., Arias-Ortiz, A., Bai, L., Baldock, J., Bedulli, C., et al. (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. Nat. Commun. *10*, 4313. https://doi.org/10.1038/s41467-019-12176-8.
12. Villa, J.A., and Bernal, B. (2018). Carbon sequestration in wetlands, from science to practice: an overview of the biogeochemical process, measurement methods, and policy framework. Ecol. Eng. *114*, 115–128. https://doi.org/10.1016/j.ecoleng.2017.06.037.
13. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (2014). 2013 Supplement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC).
14. United Nations Environment Programme (UNEP) (2020). Out of the blue: The value of seagrasses to the environment and to people (UNEP).
15. Davidson, N.C. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshw. Res. *65*, 934–941. https://doi.org/10.1071/MF14173.
16. Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marbà, N., et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One *7*, e43542. https://doi.org/10.1371/journal.pone.0043542.
17. Macreadie, P.I., Costa, M.D.P., Atwood, T.B., Friess, D.A., Kelleway, J.J., Kennedy, H., Lovelock, C.E., Serrano, O., and Duarte, C.M. (2021). Blue carbon as a natural climate solution. Nat. Rev. Earth Environ. *2*, 826–839. https://doi.org/10.1038/s43017-021-00224-1.
18. Zeng, Y., Friess, D.A., Sarira, T.V., Siman, K., and Koh, L.P. (2021). Global potential and limits of mangrove blue carbon for climate change mitigation. Curr. Biol. *31*, 1737–1743.e3. https://doi.org/10.1016/j.cub.2021.01.070.
19. Martin, A., Landis, E., Bryson, C., Lynaugh, S., Mongeau, A., and Lutz, S. (2016). Blue Carbon - Nationally Determined Contributions Inventory. Appendix to: Coastal Blue Carbon Ecosystems. Opportunities for Nationally Determined Contributions (GRID Arendal).
20. Saunders, M.I., Doropoulos, C., Bayraktarov, E., Babcock, R.C., Gorman, D., Eger, A.M., Vozzo, M.L., Gillies, C.L., Vanderklift, M.A., Steven, A.D.L., et al. (2020). Bright spots in coastal marine ecosystem restoration. Curr. Biol. *30*, R1500–R1510. https://doi.org/10.1016/j.cub.2020.10.056.
21. Contreras, C., and Thomas, S. (2019). The role of local knowledge in the governance of blue carbon. J. Indian Ocean Reg. *15*, 213–234. https://doi.org/10.1080/19480881.2019.1610546.
22. Vierros, M. (2017). Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. Clim. Change *140*, 89–100. https://doi.org/10.1007/s10584-013-0920-3.
23. Folke, C. (2004). Traditional knowledge in Social–Ecological systems. Ecol. Soc. *9*, 7. https://doi.org/10.5751/ES-01237-090307.
24. Thomas, S. (2014). Blue carbon: knowledge gaps, critical issues, and novel approaches. Ecol. Econ. *107*, 22–38. https://doi.org/10.1016/j.ecolecon.2014.07.028.
25. Song, A.M., Dressler, W.H., Satizabal, P., and Fabinyi, M. (2021). From conversion to conservation to carbon: the changing policy discourse on mangrove governance and use in the Philippines. J. Rural Stud. *82*, 184–195. https://doi.org/10.1016/j.jrurstud.2021.01.008.
26. Bennett, N.J., Blythe, J., White, C.S., and Campero, C. (2021). Blue growth and blue justice: ten risks and solutions for the ocean economy. Mar. Policy *125*, 104387. https://doi.org/10.1016/j.marpol.2020.104387.
27. Thompson, B.S., Primavera, J.H., and Friess, D.A. (2017). Governance and implementation challenges for mangrove forest Payments for Ecosystem Services (PES): empirical evidence from the Philippines. Ecosyst. Serv. *23*, 146–155. https://doi.org/10.1016/j.ecoser.2016.12.007.
28. Herr, D., von Unger, M., Laffoley, D., and McGivern, A. (2017). Pathways for implementation of blue carbon initiatives. Aquat. Conserv. Mar. Freshw. Ecosyst. *27*, 116–129. https://doi.org/10.1002/aqc.2793.
29. Torabi, N., Mata, L., Gordon, A., Garrard, G., Wescott, W., Dettmann, P., and Bekessy, S.A. (2016). The money or the trees: what drives landholders' participation in biodiverse carbon plantings? Glob. Ecol. Conserv. *7*, 1–11. https://doi.org/10.1016/j.gecco.2016.03.008.
30. Boer, H.J. (2018). The role of government in operationalising markets for REDD+ in Indonesia. For. Policy Econ. *86*, 4–12. https://doi.org/10.1016/j.forpol.2017.10.004.
31. Macreadie, P.I., Nielsen, D.A., Kelleway, J.J., Atwood, T.B., Seymour, J.R., Petrou, K., Connolly, R.M., Thomson, A.C.G., Trevathan-Tackett, S.M., and Ralph, P.J. (2017). Can we manage coastal ecosystems to sequester more blue carbon? Front. Ecol. Envir. *15*, 206–213. https://doi.org/10.1002/fee.1484.
32. Luisetti, T., Ferrini, S., Grilli, G., Jickells, T.D., Kennedy, H., Kroger, S., Lorenzoni, I., Milligan, B., van der Molen, J., Parker, R., et al. (2020). Climate action requires new accounting guidance and governance frameworks to

manage carbon in shelf seas. Nat. Commun. *11*, 4599. https://doi.org/10.1038/s41467-020-18242-w.

33. Rogers, K., Kelleway, J.J., Saintilan, N., Megonigal, J.P., Adams, J.B., Holmquist, J.R., Lu, M., Schile-Beers, L., Zawadzki, A., Mazumder, D., and Woodroffe, C.D. (2019). Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature *567*, 91–95. https://doi.org/10.1038/s41586-019-0951-7.
34. Kulp, S.A., and Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. *10*, 4844. https://doi.org/10.1038/s41467-019-12808-z.
35. Australian Government Clean Energy Regulator (2022). Carbon Credits (Carbon Farming Initiative — Tidal Restoration of Blue Carbon Ecosystems), Methodology Determination. F2022L00046. https://www.legislation.gov.au/Details/F2022L00046.
36. Climate Policy Initiative (CP) (2020). Updated View of the Global Landscape of Climate Finance 2019. https://www.climatepolicyinitiative.org/publication/updated-view-on-the-global-landscape-of-climate-finance-2019.
37. World Economic Forum (WEF) (2020). The future of nature and business. In New Nature Economy Reports (World Economic Forum (WEF)) https://www3.weforum.org/docs/WEF_The_Future_Of_Nature_And_Business_2020.pdf.
38. Kroeger, K.D., Crooks, S., Moseman-Valtierra, S., and Tang, J. (2017). Restoring tides to reduce methane emissions in impounded wetlands: a new and potent Blue Carbon climate change intervention. Sci. Rep. *7*, 11914. https://doi.org/10.1038/s41598-017-12138-4.
39. Ogar, E., Pecl, G., and Mustonen, T. (2020). Science must embrace traditional and indigenous knowledge to solve our biodiversity crisis. One Earth *3*, 162–165. https://doi.org/10.1016/j.oneear.2020.07.006.
40. Canning, A.D., Jarvis, D., Costanza, R., Hasan, S., Smart, J.C.R., Finisdore, J., Lovelock, C.E., Greenhalgh, S., Marr, H.M., Beck, M.W., et al. (2021). Financial incentives for large-scale wetland restoration: beyond markets to common asset trusts. One Earth *4*, 937–950. https://doi.org/10.1016/j.oneear.2021.06.006.
41. Engel, S., Pagiola, S., and Wunder, S. (2008). Designing payments for environmental services in theory and practice: an overview of the issues. Ecol. Econ. *65*, 663–674. https://doi.org/10.1016/j.ecolecon.2008.03.011.
42. Australian Land Conservation Alliance (ALCA) (2018). Expanding Finance Opportunities to Support Private Land Conservation in Australia (Australian Land Conservation Alliance (ALCA)). https://www.conservationfinancenetwork.org/sites/default/files/2020-05/Conservation-Finance-Scoping-Paper-30-October-2018%20%281%29.pdf.
43. Vanderklift, M.A., Marcos-Martinez, R., Butler, J.R.A., Coleman, M., Lawrence, A., Prislan, H., Steven, A.D.L., and Thomas, S. (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. Mar. Policy. *107*, 103429. https://doi.org/10.1016/j.marpol.2019.02.001.
44. Robertson, M., BenDor, T.K., Lave, R., Riggsbee, A., Ruhl, J.B., and Doyle, M. (2014). Stacking ecosystem services. Front. Ecol. Envir. *12*, 186–193. https://doi.org/10.1890/110292.
45. Zhao, C., Liu, S., Jiang, Z., Wu, Y., Cui, L., Huang, X., et al. (2019). Nitrogen purification potential limited by nitrite reduction process in coastal eutrophic wetlands. Science of the Total Environment *694*, 133702.
46. Jänes, H., Macreadie, P.I., Zu Ermgassen, P.S.E., Gair, J.R., Treby, S., Reeves, S., et al. (2020). Quantifying fisheries enhancement from coastal vegetated ecosystems. Ecosystem Services *43*, 101105.
47. Sutton-Grier, A.E., Wowk, K., and Bamford, H. (2015). Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ. Sci. Policy *51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006.
48. Waryszak, P., Gavoille, A., Whitt, A.A., Kelvin, J., and Macreadie, P.I. (2021). Combining gray and green infrastructure to improve coastal resilience: lessons learnt from hybrid flood defenses. Coastal Eng. J. *63*, 335–350. https://doi.org/10.1080/21664250.2021.1920278.
49. Ioannou, E., and Roussis, V. (2009). Natural products from seaweeds. In Plant-derived Natural Products, A. Osbourn and V. Lanzotti, eds. (Springer). https://doi.org/10.1007/978-0-387-85498-4_2.
50. Locatelli, T., Binet, T., Kairo, J.G., King, L., Madden, S., Patenaude, G., Upton, C., and Huxham, M. (2014). Turning the tide: how blue carbon and payments for ecosystem services (PES) might help save mangrove forests. Ambio *43*, 981–995. https://doi.org/10.1007/s13280-014-0530-y.
51. Websites: Verra. Climate, Community & Biodiversity Standards. https://verra.org/project/ccb-program.
52. Websites: South Pole (2022). Investments in Biodiversity. https://www.southpole.com/sustainability-solutions/investments-in-biodiversity.
53. Sippo, J.Z., Maher, D.T., Tait, D.R., Holloway, C., and Santos, I.R. (2016). Are mangroves drivers or buffers of coastal acidification? Insights from alkalinity and dissolved inorganic carbon export estimates across a latitudinal transect. Glob. Biogeochem. Cycles *30*, 753–766. https://doi.org/10.1002/2015GB005324.
54. Ortega, A., Geraldi, N.R., and Duarte, C.M. (2020). Environmental DNA identifies marine macrophyte contributions to Blue Carbon sediments. Limnol. Oceanogr. *65*, 3139–3149. https://doi.org/10.1002/lno.11579.
55. Macreadie, P.I., Serrano, O., Maher, D.T., Duarte, C.M., and Beardall, J. (2017). Addressing calcium carbonate cycling in blue carbon accounting. Limnology Oceanography Lett. *2*, 195–201. https://doi.org/10.1002/lol2.10052.
56. Kelleway, J.J., Serrano, O., Baldock, J.A., Burgess, R., Cannard, T., Lavery, P.S., et al. (2020). A national approach to greenhouse gas abatement through blue carbon management. Glob. Environ. Change *63*, 102083. https://doi.org/10.1016/j.gloenvcha.2020.102083.
57. Geraldi, N.R., Ortega, A., Serrano, O., Macreadie, P.I., Lovelock, C.E., Krause-Jensen, D., Kennedy, H., Lavery, P.S., Pace, M.L., Kaal, J., and Duarte, C.M. (2019). Fingerprinting blue carbon: rationale and tools to determine the source of organic carbon in marine depositional environments. Front. Mar. Sci. *6*, Unsp 263. https://doi.org/10.3389/fmars.2019.00263.
58. Liu, X., Dunne, J.P., Stock, C.A., Harrison, M.J., Adcroft, A., and Resplandy, L. (2019). Simulating water residence time in the coastal ocean: a global perspective. Geophys. Res. Lett. *46*, 13910–13919. https://doi.org/10.1029/2019GL085097.
59. Cisneros-Montemayor, A.M., Moreno-Baez, M., Voyer, M., Allison, E.H., Cheung, W.W.L., Hessing-Lewis, M., Oyinlola, M.A., Singh, G.G., Swartz, W., and Ota, Y. (2019). Social equity and benefits as the nexus of a transformative Blue Economy: a sectoral review of implications. Mar. Policy *109*, 103702. https://doi.org/10.1016/j.marpol.2019.103702.
60. Bell-James, J., Fitzsimons, J.A., Gillies, C.L., Shumway, N., and Lovelock, C.E. (2022). Rolling covenants to protect coastal ecosystems in the face of sea-level rise. Conservation Sci. Pract. *4*, e593. https://doi.org/10.1111/csp2.593.
61. Smith, A.J., and Kirwan, M.L. (2021). sea level-driven marsh migration results in rapid net loss of carbon. Geophys. Res. Lett. *48*. e2021GL092420. https://doi.org/10.1029/2021GL092420.
62. Doughty, C.L., Langley, J.A., Walker, W.S., Feller, I.C., Schaub, R., and Chapman, S.K. (2016). Mangrove range expansion rapidly increases coastal wetland carbon storage. Estuar. Coasts *39*, 385–396. https://doi.org/10.1007/s12237-015-9993-8.
63. Kelleway, J.J., Saintilan, N., Macreadie, P.I., Skilbeck, C.G., Zawadzki, A., and Ralph, P.J. (2016). Seventy years of continuous encroachment substantially increases 'blue carbon' capacity as mangroves replace intertidal salt marshes. Glob. Change Biol *22*, 1097–1109. https://doi.org/10.1111/gcb.13158.
64. Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., et al. (2021). Protecting the global ocean for biodiversity, food and climate. Nature *592*, 397–402. https://doi.org/10.1038/s41586-021-03371-z.
65. Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., et al. (2017). Marine reserves can mitigate and promote adaptation to climate change. Proc. Natl. Acad. Sci. U S A. *114*, 6167–6175. https://doi.org/10.1073/pnas.1701262114.
66. Mariani, G., Cheung, W.W.L., Lyet, A., Sala, E., Mayorga, J., Velez, L., Gaines, S.D., Dejean, T., Troussellier, M., and Mouillot, D. (2020). Let more big fish sink: fisheries prevent blue carbon sequestration—half in unprofitable areas. Sci. Adv. *6*, eabb4848. https://doi.org/10.1126/sciadv.abb4848.