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Perspective
Adaptation and Carbon Removal

Holly J. Buck,[1,2,*] Jay Furhman,[3] David R. Morrow,[4] Daniel L. Sanchez,[5] and Frances M. Wang[6]
[1]UCLA Institute of the Environment and Sustainability, Los Angeles, CA, USA
[2]Department of Environment and Sustainability, University at Buffalo, Buffalo, NY, USA
[3]Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA, USA
[4]Institute for Carbon Removal Law and Policy, American University, Washington, DC, USA
[5]Department of Environmental Science, Policy, and Management, University of California-Berkeley, Berkeley, CA, USA
[6]ClimateWorks Foundation, San Francisco, CA, USA
*Correspondence: hbuck2@buffalo.edu
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SUMMARY

Carbon dioxide removal and climate change adaptation are rarely analyzed together, yet it is critical to consider the interactions between these forms of climate response. We identify ways to foreground adaptation in carbon removal policies and project designs and to incorporate carbon removal into adaptation efforts. Attempts at aligning adaptation and carbon removal may genuinely increase adaptive capacity or introduce new vulnerabilities, depending on policy and project design. Based upon four case studies of addressing adaptation needs with adaptive carbon removal, we find that effective implementation is likely to hinge upon predictable climate policy, innovative technical policies such as rigorous life-cycle assessment, and project design with local ecological conditions in mind. We propose three simple principles for integrating carbon removal and adaptation: identify opportunities for adaptive carbon removal in planning, prioritize adaptive value of projects, and give credit for carbon removed.

INTRODUCTION

Carbon dioxide removal (CDR) is increasingly joining mitigation and adaptation in the climate response portfolio. Significant amounts of carbon removal will be necessary to limit warming to 1.5°C, through a diverse suite of approaches, some of which are ready to deploy today and others that could be ready to deploy on a large scale by mid-century.[1] Most scenarios for achieving 2°C also rely on large-scale carbon removal.[2] Many nations, such as the United Kingdom and France, have set net-zero emissions targets, with over 60 countries pledging to do so; the state of California has also set a target of carbon neutrality by 2045, and countries such as Sweden are explicitly adopting the goal of being carbon-negative. To rapidly achieve net zero, most scenarios assume some removal capacity to compensate for residual emissions from sectors that are deemed difficult to mitigate.[1] As CDR increasingly becomes an imperative, with maturing approaches entering early-stage deployment, scientists and analysts have begun to explore interactions between carbon removal and mitigation, including whether carbon removal will deter mitigation,[3–6] carbon capture and use as part of decarbonization,[7–9] and how carbon removal could work with mitigation in the context of energy systems.[10–13]

Despite the attention given to carbon removal in mitigation, researchers and policymakers have scarcely discussed the interactions between carbon removal and adaptation. We lack both generalized theory on these interactions and specific case studies through which to examine them. Possible reasons for this lacuna include: (1) the scholarly communities studying carbon removal and mitigation may be closer, as researchers of "deep decarbonization," than the communities studying carbon removal and adaptation; (2) many carbon removal technologies are immature, leaving a limited evidence base for understanding carbon removal-adaptation interactions; and (3) deterrence effects are more obvious between carbon removal and mitigation than with adaptation. Moreover, in some cases, papers that explore the practices and synergies may not use the terminology of carbon removal or adaptation, focusing on single strategies such as soil carbon sequestration or groupings such as natural climate solutions, rather than umbrella terminology.[14]

Consideration of carbon removal and adaptation together is currently limited to two places: the discussion of "ecosystem-based adaptation," in which ecological processes and habitats are sustainably managed as part of adaptation strategies,[15,16] and the discussion of social "co-benefits" of carbon removal techniques,[17,18] of which adaptation could be one. These publications—which are often searching for "win-win" situations[19]—are informative, but do not explore the full range of interactions between the two responses. As the field of carbon removal advances, a systematic framework for exploring carbon removal-adaptation interactions is needed.

There are important reasons for both science and policy to consider carbon removal and adaptation together at this moment. Perhaps the most important benefit of joint analysis is that the literature on adaptation emphasizes the social aspects of climate response, which are often missing from analyses of the technical potentials of carbon removal. Vulnerability analysis considers why people are at risk, which draws attention to social conditions—conditions that would also influence and be influenced by carbon removal deployment. Evaluating carbon removal within adaptation frameworks can help clarify the social contexts of carbon removal technologies and aid in formulating

policy for carbon removal that addresses existing and new vulnerabilities. Right now, there are calls to research a portfolio of carbon removal techniques,[2,20] yet it is not clear how each approach will fit into this portfolio, or which technologies and practices are included. Scholarship on the interactions with adaptation can help inform the design of this portfolio and aid in anticipatory governance.

In this Perspective, we aim to establish a framework for future research on the interactions between carbon removal and adaptation. We make recommendations for when and how to pursue adaptive carbon removal, meaning practices that remove carbon from the atmosphere while providing adaptation benefits and reducing vulnerability. Note that whether adaptive carbon removal activities can be considered as providing "negative emissions" or contributing toward "climate-restorative" adaptation goals depends on particular design choices, such as the life-cycle analysis of particular projects.[21] As our recommendations emphasize, just because an adaptation project is carbon-negative does not mean that communities or policymakers ought to prefer it over another project that reduces vulnerability more effectively.

ASSESSING CARBON REMOVAL AND ADAPTATION TOGETHER

Learning from Adaptation Thinking

Adaptation was not always a pillar of climate response. Like carbon removal, adaptation was initially viewed as marginal in climate policy, until the implications of not meeting mitigation goals became increasingly clear. Adaptation was slow to be discussed in the first decade of United Nations Framework Convention on Climate Change negotiations, as it was seen to carry the risk of substituting for mitigation. In the first Intergovernmental Panel on Climate Change (IPCC) assessment report, in 1990, the focus was on vulnerability, framed primarily in terms of exposure to impacts on particular sectors.[22] In the early 2000s, the focus shifted from vulnerability (cause-focused) to adaptation (response-focused). Adaptation was defined in 2001 by the IPCC as "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities."[23] It only became an equal pillar to mitigation as part of a "framework" in 2007 and beyond.[24,25] Adaptation referred to a collection of practices, technologies, programs, or policies implemented to reduce the impact of climate hazards. Critiques of this politically neutral concept of adaptation have discussed how it can exclude the possibility of non-adaptation from consideration and how it can obscure causality and naturalize the problem, placing the risk within climate rather than society.[26]

More recently, though, practitioners and scholars have embraced broader discourses of resilience and transformative adaptation, or adaptation that addresses the roots of vulnerability through changing fundamental socioeconomic system attributes.[27] Adaptation has also moved from being seen as local to requiring global response. In 2015, Article 7 of the Paris Agreement set out several provisions for adaptation, including a "global goal" that recognizes adaptation as a global challenge. This opened up the possibility of new institutions, processes, and actors to govern it on a global scale.[22] Carbon removal can also be seen as a collection of local projects and initiatives,[28] but one whose regulation and incentivization may benefit from global governance, for similar reasons.

What does thinking about vulnerability, resilience, transformational adaptation, and global-scale climate response do for our thinking about carbon removal? First, a few decades of scholarship on adaptation highlight the vulnerabilities that can be exacerbated or created within climate solutions themselves. Climate change requires adaptation not only to new hazards and resource constraints but also to changes in resource access as well as new regimes of knowledge and information.[25] Climate change may, thus, require communities to adapt to carbon removal regimes, which would introduce new knowledge practices, and could either increase or diminish local control over resources. Previous research on "carbon logics" in biodiversity has traced how various actors see financing opportunities for framing conservation actions through carbon and carbon markets, while others see the logic of making decisions based upon carbon analyses as a threat to effective conservation.[29] This illustrates the risk of "carbon logics" similarly being imposed upon adaptation, which like biodiversity is underfunded relative to the challenge: carbon removal may be seen as some as a way to access more financing opportunities, while others may identify the influence of carbon analyses in decision-making as a threat to effective adaptation.

The adaptation literature also introduces the concept of "double exposure," whereby communities experience exposure to both climate change and economic globalization, and hence there are new global drivers to climate vulnerability.[30] Carbon removal interacts with this double exposure in that some carbon removal components, such as biofuels (which could be part of negative emissions when coupled with carbon capture and storage), have global supply chains and impacts on global commodity prices. Financial carbon removal products such as carbon removal certificates may also have global dimensions, depending on their design and mechanism of exchange.

Second, and related to these new vulnerabilities, the adaptation literature helps to bring the issue of agency into sharper focus: who proposes interventions, and who has authority to implement them? Carbon removal and adaptation are both intentional social responses, and they bring up the question of public benefit from these actions. On one hand, it is not reasonable to ask individuals and small communities to organize responses to large-scale problems—adaptation scholar Jesse Ribot points out national defense, road and rail transport systems, and hurricane preparedness as examples for which society reasonably expects governments to do the heavy lifting of organization and repair.[25] On the other hand, when adaptation actions are formal public sector interventions to address specific risks, they can reinforce the authority of policymakers and experts who are designing and engineering the adaptation.[26] Moreover, adaptation activities implemented by people outside the community can result in maladaptation because of a lack of knowledge of local contexts. There is a tension here, then, between the responsibility of government to take on large-scale, complex responses and the way in which those can hinder local agency—much like with carbon removal.

Opportunities along the Adaptation Continuum

Assessing carbon removal policies and practices with these concepts from adaptation in mind helps us see dimensions of public benefit, agency and authority, vulnerability, and transformation that are often underemphasized in carbon removal discussions. In mapping opportunities for synergies, we consider them first through the lens of carbon removal practices, and second through the lens of adaptation need.

In Table 1, we draw upon a simplified version of a framework from the adaptation literature: the adaptation continuum, based on a 2007 report by Heather McGray and colleagues at the World ResourcesInstitute.[31] This continuum was developed to address the full spectrum of adaptation actions and to help think about how to mainstream adaptation into development. On one side, there are actions that address drivers of vulnerability. On the other are actions that are intended to address climate impacts, and in the original version there are efforts around building the capacity to respond to climate change and manage climate risk, included here in the left-hand column. When it comes to incorporating carbon removal into adaptation, this is a useful framing tool in terms of examining the range of adaptive practices, and which particular designs of carbon removal implementation might be reasonably regarded as adaptation.

A key insight here is that the potential for carbon removal interventions to increase adaptive capacity lies in the implementation; it is not inherent in the technology itself. Much of the adaptive benefit of the carbon removal practices lies not in addressing climate impacts, but in building up response capacity—such as new knowledge networks and new sources of data—and in addressing the drivers of vulnerability through new economic opportunities. These are benefits that are not guaranteed to arise in every carbon removal implementation; they require careful policy and project design.

Maladaptive Instances of Carbon Removal

What is clear from Table 1 is the amount of political work needed to enact the best-case scenarios with regard to adaptive carbon removal. The risk of poor policy is not just the failure to capture opportunities but the prospect of decreasing adaptive capacity.

When it comes to adaptation, there are many ways in which adaptation activities can actually lower a system's ability to adapt to climate change. One framework, sketched out by Benjamin Sovacool and illustrated with examples from adaptation projects in Bangladesh, examines how adaptation activities can constitute enclosure (capturing resources or authority), exclusion (marginalizing stakeholders), encroachment (ecological damage), and entrenchment (worsening social inequality).[32] An extreme example is what Kasia Paprocki calls "anticipatory ruination," in her analysis of shrimp cultivation in Bangladesh: the expansion of shrimp aquaculture in southwestern Bangladesh, promoted as an anticipatory adaptive response to rising sea levels, has brought social and ecological destruction in its wake, rendering other futures, such as rice farming, unviable.[33] Indeed, both mitigation and adaptation have been linked to exacerbating social and ecological threats, including environmentally induced displacement from forest carbon, biofuel, or climate-related development projects,[34,35] agrarian institutions that create new political vulnerabilities for the rural poor,[36] or adaptation projects that redistribute vulnerability more generally.[37,38] Carbon removal practices could also result in these failure modes. These risks need to be kept in mind when it comes to making carbon removal policy. A first step is mapping the possible maladaptations.

Table 2 illustrates that most of the carbon removal practices do not directly create ecological hazards. Rather, their potential influence on the climate system has to do with difficult-to-quantify tradeoffs and mitigation deterrence effects of poor implementation (i.e., is the carbon removal practice poorly regulated so that its life-cycle analysis is actually emissive rather than negative, or does the removal practice substitute for other alternatives that may have a greater climate benefit?) A key finding of this analysis is that practices may look like "no-regrets" actions when considered through the exclusive lens of climate impacts, but may have maladaptive instances when looking at the broader continuum of vulnerability.

EXPLORING ADAPTIVE CARBON REMOVAL THROUGH CASE STUDIES

To explore how adaptation challenges can be either addressed or exacerbated by including carbon removal into adaptation actions, we draw on four case studies. These cases, while hypothetical, provide a rich qualitative and quantitative prompt regarding the potential implementation of adaptive carbon removal strategies. Cases were chosen to reflect a diversity of adaptation needs, geographies, and carbon removal approaches (Box 1).

Several preliminary lessons emerge from these cases. First, adaptive carbon removal projects and policies must be designed with local ecological conditions in mind in order to maximize adaptation benefits. For example, afforestation can increase severe wildfire risks in California's fire-prone, temperate forests. Severe wildfires, resulting in part from both climate change and lack of management, increase the likelihood of large carbon losses, and loss of life and property.[39] This stands in contrast to the well-documented carbon storage and co-benefits of afforestation in other ecosystems.

Second, implementation of CDR-adaptation solutions often requires new technical policies, such as rigorous quantification and permanence methodologies for performance-based subsidies for low-carbon or carbon-negative fuels as part of direct air capture policy. We need policies that set regulatory standards for life-cycle analysis, taking account of permanence concerns. Some of these policies and methodologies will be new, and should be crafted to be easily legible to policymakers and communities of interest who are thinking about both adaptation and carbon removal as goals. Consider forest management and innovative wood products, which we deem an opportunity for adaptive carbon removal (Note S1, "Carbon dioxide removal as a component of climate-beneficial forest management"). To align adaptation needs with climate change mitigation, policy must ensure the climate benefits of wood products sourced from sustainably managed forests. CDR technologies could play an important role in ensuring that fuel treatments also sequester carbon in Californian forests.[39] To achieve carbon removal from forest biomass, California policymakers should effectively account for forest carbon sequestration in products and provide policy signals for climate-restorative land

Table 1. Opportunities for Carbon Removal Practices to Address Vulnerability and Climate Impacts

Carbon Removal Practice	Opportunities to Address Drivers of Vulnerability and Build Response Capacity	Opportunities to Confront Climate Impacts
BECCS/Biochar/mass timber	• Rural economic development through the "circular carbon economy"/bioeconomy • Knowledge networks built around carbon management (e.g., cooperative extension, regional conservation districts, forestry sector, waste management) • Robust food/fiber supply chain management to better track carbon	• Perennialization of agriculture for new bioenergy crops • Fire and mortality-adapted forests • Healthy soils with char amendments
Accelerated weathering/alkaline waste streams/ocean alkalinity	• Diversification of livelihood for communities where minerals could be mined • Training to improve soil health with soil amendments, integrated into soil health assistance • Tracking application of crushed basalt to agricultural land could be done simultaneously with advice on other inputs for best yields under climate change • New research networks can add understanding to oceanic impacts of climate change	• Potential to use bulk materials for coastal fortification and to mitigate coastal erosion • Reducing impacts of ocean acidification (protecting corals and other calcifying organisms)
DAC/geological sequestration	• Diversify livelihood for people in areas of geological sequestration; potential for just transition away from high polluting industry jobs • Training for workers currently engaged in fossil fuel extraction to create a community of practice on carbon management • DAC with CO_2-EOR could encourage a framework for thinking and tracking emissions associated with the production of fossil fuels; calculation of corresponding effort to remove specific amounts of CO_2 could force consideration of production decisions	• No immediate local reduction of climate impacts; potential for reduction of various global climate impacts if implemented on a scale large enough to reduce greenhouse gas concentrations
Soil carbon sequestration	• Potential for additional source of on-farm revenue for carbon • Regenerative farming systems have multiple products, enabling diversification of farm income • Social networks around regenerative farming - direct markets for regeneratively grown products can help share knowledge about dealing with climate stressors • Platforms for soil carbon monitoring could be dual-purposed to also advise on climate risk	• Increased soil permeability to cope with flooding; potential for regional cooling due to increased soil moisture • Increased soil moisture to increase drought resilience

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Table 1. *Continued*

Carbon Removal Practice	Opportunities to Address Drivers of Vulnerability and Build Response Capacity	Opportunities to Confront Climate Impacts
Coastal blue carbon	• Potential additional revenue source and employment for coastal communities • Participatory wetland protection/ restoration practices can build capacity to engage with other climate-related threats to coastal ecosystems and communities • Monitoring of coastal blue carbon could be used in planning and permitting decisions	• Flood protection
Afforestation/reforestation	• Additional source of revenue for forestry communities and land-holders, for forest carbon as well as sustainably managed multi-species wood products • Networks of forest industries, land managers, and forest users can strengthen collaboration on other aspects of forest stew-ardship • Better accounting of forest car-bon could be used in forest man-agement decisions	• Local cooling benefits; urban afforestation can provide shade trees in heat stressed areas; • Improved water security; erosion control in the face of heavy pre-cipitation events
Agroforestry	• Diversification of livelihoods • farm group membership and expanded extension networks may provide additional sources of information on climate adaptation for farmers	• Providing shade on agricultural lands; water benefits; soil health improvement; windbreaks • Identification of climate resilient, high-value trees can help farmers in coping with drought

BECCS, bioenergy with carbon capture and storage; DAC, direct air capture; EOR, enhanced oil recovery.

management.[40] California's low-carbon fuels standard, which was recently revised to account for the climate benefits of carbon capture and sequestration, could play an important role as a niche market for CDR technologies such as bioenergy with carbon capture and storage (BECCS), which can produce carbon-negative fuels, as well as for direct air capture.[39]

Third, in cases where the adaptive value of carbon removal depends critically on financial incentives to sequester carbon, reliable revenue forecasts and predictability in climate policy or carbon markets can make the difference between effective adaptation and maladaptation. With the example of reforesting spekboom thicket (Note S2), spekboom grows slowly, and potential carbon farmers need to know that carbon markets will be stable enough that long-term investments will pay off.

Finally, considering carbon removal and adaptation in parallel centers considerations of social structures, power, consent, and justice. Moreover, when there are multiple carbon-negative options for addressing a particular adaptation need, the one that sequesters the most carbon is not necessarily the best from an adaptation perspective. Table 3 presents an "adaptation-first" way of looking at the opportunities that carbon removal practices considered as part of these case studies have for adaptation. Foregrounding vulnerability and exposure reduction, adaptation, and transformation makes clear that there are many needs that carbon removal cannot address.

PRINCIPLES FOR ADAPTIVE CARBON REMOVAL

Drawing on these cases, we suggest three principles for integrating carbon removal practices into adaptation effectively.

Identify Carbon-Negative Opportunities

When developing responses to an adaptation need, communities and policymakers should recognize and assess opportunities for carbon-negative adaptation, meaning adaptation measures that capture and sequester more carbon than they emit. Rigorous systems analysis, including life-cycle assessment and supply chain optimization, can help ensure true climate benefits.[20] Of course, carbon-negative options may not be the best options for the situation.

Prioritize Adaptive Value in Choosing and Designing Projects

When choosing how to respond to a particular adaptation need, communities and policymakers should prioritize good adaptation over removing carbon. That is, in cases where

Table 2. Maladaptive Instances of Carbon Removal

Carbon Removal Practice	Exacerbating Drivers; Decreasing Response Capacity	Exacerbating Climate Impacts
BECCS/Biochar/mass timber	• Bioenergy crops on land that is marked as "marginal" but was in fact being used by communities • Bioenergy crop production arrangements that enroll farmers in disfavorable contract farming schemes • enclosure of communally used forests for plantation crops, and other land tenure impacts • BECCS deployed in fragmented manner, without consideration of various actors in supply chains • Failure to track BECCS life-cycle emissions—limiting international accreditation and confidence in the approach, as well as poor climate outcomes	• Land management practices that increase drought, such as improper biomass species adoption • Increased food security risks
Accelerated weathering (AW)/alkaline waste streams/ocean liming	• Entrenching social inequalities, such as gender inequalities, in mining communities • Control over AW processes by mining corporations with low social license, limiting participation • Failure to study AW applications and accurately model removals	• Few direct climate impacts on land; potential for indirectly increased emissions from poor implementation
DAC/geological sequestration	• Energy needs of DAC could upset energy availability • Fiscal cost could also fall upon vulnerable people • If DAC is articulated and coordinated by existing startups and fossil fuel companies, limited capacity for public participation • Failure to track DAC-EOR life-cycle emissions—limiting international accreditation and confidence in the approach, as well as poor climate outcomes	• Few direct climate impacts; potential for indirectly increased emissions from poor implementation
Soil carbon sequestration	• If incentive programs begin and then fail to be maintained, farmers could end up more vulnerable, e.g., in debt due to new equipment • If implementation is concentrated in the private sector, potential for reduced knowledge sharing about farmer practices • Failure to accurately track carbon emissions could limit confidence in the approach	• Few direct climate impacts; potential for indirectly increased emissions from poor implementation • Increased food security risks with poor implementation (e.g., yield decrease)
Coastal blue carbon	• Land/water access could be constrained for blue carbon conservation projects, impacting livelihoods • Blue carbon projects without local participation could disempower local communities • Blue carbon projects without attention to climate projects could end up being implemented in places where they will fail due to climate conditions	• Few direct climate impacts; potential for indirectly increased emissions from poor implementation

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Table 2. *Continued*

Carbon Removal Practice	Exacerbating Drivers; Decreasing Response Capacity	Exacerbating Climate Impacts
Afforestation/reforestation	• Land access could be constrained for afforestation projects, impacting livelihoods; "marginal" lands for afforestation could be incorrectly identified • Land tenure/new enclosures change social relations and decrease the capacity of the community to work together on climate response; gendered or class impacts to new forest carbon enclosures	• Few direct climate impacts; potential for indirectly increased emissions from poor implementation; afforestation at high latitudes could increase warming by changing albedo • Changes in forest management could increase fire risk • Monoculture "carbon plantations" could increase other climate-mediated threats to forests, such as insects, and exacerbate climate risks to biodiversity
Agroforestry	• Most vulnerable farmers can lack the resources to adopt agroforestry, deepening social divides • Trees not adapted to climate change may result in lost profits for landholders	• Few direct climate impacts; potential for indirectly increased emissions from poor implementation

the (most) carbon-negative response is not the best response from an adaptation perspective, communities and policymakers should choose the most adaptive one, not the (most) carbon-negative one. When policymakers are choosing between carbon removal measures, they should consider the benefits and risk to adaptation of each. Part of this weighing involves prioritizing projects that are environmentally just—where vulnerable communities experience benefits from the adaptation projects, and not additional risks from them—and rejecting projects that may look adaptive and carbon-negative but only serve some; this is what we mean by "good adaptation."

Give Credit where Credit Is Due

When communities, cities, or states do implement carbon-negative adaptation measures, they should get credit for the carbon they remove, as allowed under relevant policy instruments (e.g., by counting that sequestered carbon toward relevant policy targets or via economic incentives). This could work in a positive feedback loop to strengthen adaptive capacity. Part of "giving credit" also involves explicitly rewarding projects that create co-benefits and valuing these co-benefits.

Figure 1 illustrates the application of these principles. Note that the first two principles serve primarily to guide decision makers at more local levels, where decisions about specific adaptation projects are generally made, whereas the third principle will generally operate at higher levels of governance, where incentive structures and accounting mechanisms are generally made. For instance, a rural community in South Africa trying to decide how to adapt to increased variability in precipitation could seek out carbon-negative options and then decide for themselves whether approaches that sequester carbon rapidly, such as planting spekboom, constitute the most adaptive response, but policymakers at the provincial, national, or international level would need to set up mechanisms to acknowledge and reward those communities for the carbon they capture.

PUTTING THESE PRINCIPLES INTO ACTION: GOVERNANCE NEEDS

What will it take to put these principles into practice? Adaptation is context-specific, and adaptation governance is polycentric and multiscalar.[41] This means that actors seeking to implement adaptive carbon removal can benefit from policy innovation and policy diffusion at multiple levels. Individuals, communities, cities, subnational governments, and national governments will need to identify and implement adaptive carbon removal measures that work in their specific contexts. They can learn from and teach one another about promising approaches through peer-to-peer connections (e.g., through local social networks, national networks of civil society organizations, transnational municipal networks) and through information-sharing and technical assistance across different levels (e.g., from national governments to local governments or from civil society organizations to individuals). Policymakers, investors, activists, and community organizers can encourage adaptive carbon removal by explicitly encouraging the development of such mechanisms for policy innovation and policy diffusion.

The third principle —giving credit where credit is due—is likely to prove the most challenging to implement well. "Credit," in the relevant sense, could mean simply recognizing captured carbon for regulatory purposes. Recognizing the captured carbon matters in contexts where a jurisdiction has an obligation or commitment to reduce its net greenhouse gas emissions. For instance, the Paris Agreement requires that Parties regularly provide a "national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases" (Art. 13, Para. 7(a)). A comprehensive inventory would include carbon removed by sinks that were created or enhanced for adaptation purposes, which would allow countries to count the carbon removal impacts of adaptation toward the mitigation portion of their Nationally Determined Contributions (NDCs), building on work being done by the United Nations Development Program and NGOs about best practices for including natural climate solutions in NDCs.[14] The

Box 1. Case Studies of Implementing Adaptive Carbon Removal

We examine four case studies of adaptation challenges that could be met with adaptive carbon removal (see Notes S1–S4 for full details). For each case we examine the adaptation need, alongside how inclusion of carbon removal approaches could drive adaptation benefits or maladaptation. We find that carbon removal and adaptation require interdisciplinary examination—including disparate fields such as ecology, economics, social science, and engineering—to reveal their complex interactions.

#	Case Study Title	Location	Adaptation Challenge	Adaptive Carbon Removal	Maladaptation Risks from Incorporating Carbon Removal
1	Climate-beneficial forest management to address wildfire risk	California, USA	Increased loss of life and property resulting from severe wildfire	Thinning forests and using the wood to produce carbon-negative products	Afforestation could increase fire risk, which both increases vulnerability and decreases carbon storage
2	Revegetation of degraded ecosystems with carbon-sequestering spekboom as a component of farmer adaptation to climate change	South Africa	Drought and decreased ability to cultivate crops	Revegetating indigenous plants to increase browsing for livestock	Putting effort into ecological restoration only to have policy change
3	Mitigation and adaptation tradeoffs between green and gray infrastructure projects for coastal resilience	New York City, USA	Sea level rise in urban areas	Fortifying coastlines with seawalls or natural infrastructure that sequesters carbon	Incentivizing barrier-based flood protection that transfers vulnerabilities elsewhere, or conflates global benefits of carbon removal with local benefits of adaptation
4	Economic transition, or recommitment to resource extraction? Direct air capture implementation in fossil fuel-dependent economies	Texas, USA	Economic transition away from fossil fuel production	Retraining fossil fuel industry workers for jobs in direct air capture	The possibility of further entrenching the power of fossil fuel companies

same argument for counting removals through adaptive carbon removal applies to activities within jurisdictions that have set goals to reach net-zero or net-negative emissions.

Good accounting requires that monitoring, reporting, and verification of carbon sequestration be transparent, effective, and efficient, which will be especially challenging given that many adaptive carbon removal projects would be small-scale. The polycentric approach to climate governance has opportunities for experimentation and learning,[42] and perhaps a bottom-up approach to carbon removal[28] can offer opportunities to tackle the challenges, as they are significant. First, there are basic technical challenges: for many carbon removal approaches, such as soil carbon sequestration and enhanced weathering, more robust, standardized, and accurate accounting methods still need to be developed. Second, there is the additional challenge of addressing the permanence issues and the potential reversibility of the sequestered carbon, such as when an afforested area is burned by wildfire. For instance, accounting for international trade of forest products raises numerous life-cycle accounting considerations.[43] This is not just an abstract concept. The Drax powerplant in the United Kingdom has switched from burning coal to burning wood pellets imported from southeastern United States. The company is adding carbon capture and sequestration with the goal of becoming carbon-negative.[44] The challenge of carbon accounting across such a complex supply chain, however, has provoked controversy over the ultimate climate impact of operations such as Drax's.[45–47] Similar controversies will likely arise with respect to adaptive carbon removal projects. Scientists can work with NGOs and policymakers to ensure that monitoring, reporting, and verification is as robust as possible across scales and jurisdictions.

"Giving credit" could also mean offering economic or other incentives for sequestering carbon. Thus, one critical question is whether and how national or international climate finance mechanisms, such as the European Union's Emissions Trading System, should reward carbon sequestration in adaptation projects. On the one hand, doing so risks incentivizing decisionmakers to prioritize carbon removal over adaptation, especially in contexts where the benefits of adaptation remain far in the future and the economic rewards from sequestering carbon appear quickly. For instance, emissions pricing policies alone may incentivize carbon removal largely to offset ongoing residual emissions, with enormous maladaptive direct and market-mediated side effects (e.g., water demand and food price increases from land competition for biofuels and afforestation).[48] On the other hand, carbon removal-related economic incentives could provide a much-needed additional stream of adaptation finance. One partial solution is to ensure that economic incentives go to the actors who stand to benefit most directly from the adaptation measures. For instance, if a local government adopts an agricultural extension program to encourage farmers to adopt carbon-capturing and resilience-boosting regenerative agricultural practices, payments for the captured carbon could go to the farmers themselves, not the government. The farmers could then decide for themselves whether the shift to regenerative agriculture is worthwhile on a case-by-case basis, taking into account both the

Table 3. "Adaptation-First" Mapping of Carbon Removal Practices for Adaptation and Transformation

Overlapping Approaches	Category	Examples
Vulnerability and exposure reduction	• Human development • Poverty alleviation • Livelihood security • Disaster risk management • Ecosystem management • Spatial or land use planning	• Sustainable forms of bioenergy with carbon capture and storage(case 1) could provide energy to pursue work, education, and opportunities • Potential for increased support of livestock via ecosystem restoration (case 2) • Employment opportunities for workers with industrial experience (e.g., oil and gas) for new direct air capture or geologic CO_2 storage industries (case 4) • Forest carbon mapping as part of greater forest hazard and wildfire risk mapping (case 1); coastal blue carbon programs that are designed to mitigate flood risk (case 3) • Wetland restoration (case 3) • Dryland ecosystem restoration (case 2) • Increased attention to coastal design and planning for sea level rise (case 3)
Adaptation	• Structural/physical: engineering and built environment • Structural/physical: technological options • Structural/physical: ecosystem-based options • Structural/physical: services • Institutional: economic options • Institutional: laws and regulations • Institutional: national and government policies and programs	• Carbon-negative cement for coastal protection (case 3) • Power plant/electric grid upgrades (Case 4) • Improved structural wood products (e.g., mass timber) (case 1) • Gray infrastructure for coastal resilience (case 3) • Ecological restoration (case 2) • Coastal ecosystems restoration (case 3) • Robust forest biomass supply chain management to reduce vulnerability (case 1) • Payments for ecosystem services—allowing biological carbon removal methods to qualify for carbon credits indirectly funds the ecosystems services provided as a result of ecosystem restorations (case 2) • Patent pools and technology transfer (case 4) • Building standards and codes aimed toward both embedding carbon and adaptation (case 1) • Local economy and job creation programs (case 1, case 4) • Ecosystem-based management (case 2, case 3)
Transformation	• Social: educational options • Social: informational options • Social: behavioral options • Spheres of change: practical • Spheres of change: political • Spheres of change: personal	• Knowledge-sharing and learning platforms for forest management (case 1) and ecosystem restoration (case 2) • Systematic monitoring and remote sensing for forest management (case 1) • Detailed mapping (case 3) • Adoption of transformed forest management practices (case 1) • Consumer shifts toward increased demand for low-carbon or carbon-negative products and services (case 1) • Political decisions that support sustainable, carbon-negative forms of direct air capture (case 4) • Ecosystem regeneration as a framework for understanding climate action (case 2)

financial rewards and the near- and long-term adaptation benefits.

Taken together, these three principles can help ensure that including carbon removal in adaptation will not sacrifice the actual goals of adaptation. Actively seeking out adaptive carbon removal measures and giving credit where credit is due can help encourage targeted adoption of adaptive carbon removal. The focus in adaptation efforts, however, should remain on building resilience, not on removing carbon. Adaptive carbon removal practices, if properly implemented, can align carbon removal and adaptation, strengthening the social responses to climate change and addressing factors in vulnerability.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.09.008.

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AUTHOR CONTRIBUTIONS

H.J.B., J.F., D.R.M., D.L.S., and F.M.W. contributed to the framework in the paper and the writing of the paper. H.J.B. coordinated the writing of the paper.

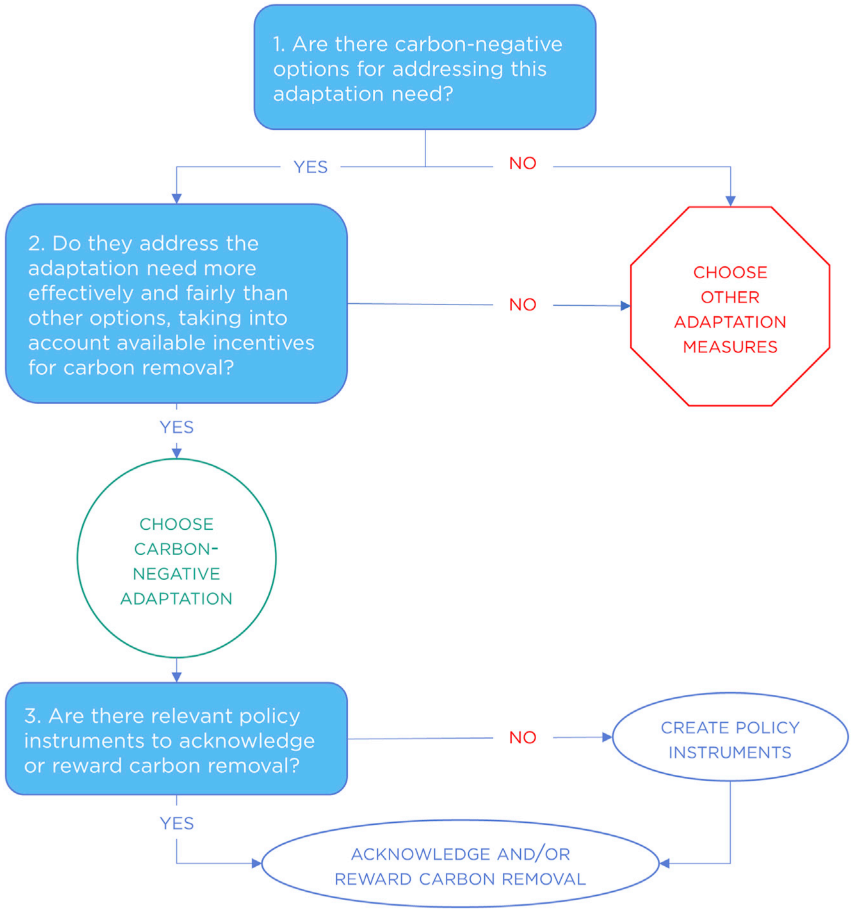

Figure 1. Flowchart Showing the Process of Implementing Genuinely Adaptive Carbon Removal Projects

Communities should (1) identify carbon-negative adaptation options, but (2) prioritize adaptation over carbon removal in choosing and designing projects, and (3) "give credit where credit is due" by acknowledging and/or rewarding carbon removal in adaptation projects, even if that means creating new policy instruments to do so.

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