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Authors
Novick, Kimberly A
Keenan, Trevor F
Anderegg, William RL
et al.

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We need a solid scientific basis for nature-based climate solutions in the United States

Kimberly A. Novick[a,1], Trevor F. Keenan[b,c], William R. L. Anderegg[d,e], Caroline P. Normile[f], Benjamin R. K. Runkle[g], Emily E. Oldfield[h], Gyami Shrestha[i], Dennis D. Baldocchi[b], Margaret E. K. Evans[j], James T. Randerson[k], Jonathan Sanderman[l], Margaret S. Torn[c,m], Anna T. Trugman[n], and Christopher A. Williams[o]

Flux towers like this one in an Arkansas rice field can help monitor methane emissions reductions strategies as part of efforts to better evaluate nature-based climate solutions. Image credit: Rory Doyle (photojournalist).

Nature-based climate solutions (NbCS) have courted both enthusiastic support and considerable controversy (1–8). Defined as deliberate human actions that manipulate ecosystems to improve the planet's greenhouse gas balance, NbCS provoke disagreement, in large part because their implementation has so far outpaced a science-based understanding of their long-term climate mitigation potential.

NbCS strategies protect carbon-dense forests and wetlands; improve the management of agricultural, forest, and grazing lands; and restore carbon-dense natural ecosystems. These actions are designed to increase carbon dioxide removal from the atmosphere and reduce ecosystem emissions of CO_2 and other greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O). Many of these strategies confer well-known environmental cobenefits (2), as well as potential economic rewards for those involved. Consequently, NbCS are backed by a broad coalition of actors, including bipartisan lawmakers, conservation groups, and the private sector. For example, tens of billions of federal dollars were recently allocated for the implementation of such projects through the Inflation Reduction Act (9). Recent initiatives like the White House "Nature-Based Solutions Roadmap" (10) promise

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[1]To whom correspondence may be addressed. Email: knovick@indiana.edu.

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future investments. Conservation groups are also spending heavily on these strategies, while private-sector participation in carbon-offset markets has grown dramatically in recent years (4).

Ambitious NbCS programs could deliver benefits for biodiversity, communities, and the climate (1, 2, 11). Unfortunately, a lack of evidence about specific benefits from specific strategies prevents researchers and policymakers from confidently prescribing when and where they should be used. Certainly, many NbCS are known to boost biodiversity, soil health, and air and water quality (1, 2). But for these strategies to meaningfully support climate mitigation at a scale that justifies the private and public investments, they must lead to significant, durable, and measurable net climate cooling that's in addition to what would have occurred anyway (4, 12). They must also do so without simply displacing emissions to other locations. Right now, we simply do not know when and where most NbCS meet these criteria (4, 5, 13).

Widespread Challenges

This challenge exists across all ecosystems. In agricultural land, we are hampered by a lack of representative data and field trials in many places, which severely limits mechanistic and practical understanding of the climate benefits of most management practices (4). In forests, we have relatively rich information on changes in tree biomass from the US Department of Agriculture (USDA) Forest Inventory and Analysis (FIA) Program and advancements in satellite tree biomass monitoring (4). But most methods to estimate carbon uptake from tree biomass data rely on decades-old empirical models that miss important ecosystem carbon sources and sinks, such as forest soils. Further, they do not account for how climate feedbacks, such as rising CO_2, temperature, and water stress, are changing patterns of carbon assimilation and allocation and increasing mortality and disturbance (14). Together, these impacts weaken the link between tree biomass growth and the carbon balance of the entire stand. In wetlands, we are further hindered by the fact that these ecosystems are extremely diverse, and it can take years of sustained change in management practices for NbCS impacts to become measurable. For all ecosystems, approaches to establish and quantify the additionality of individual NbCS projects are proliferating at a range of scales without first being benchmarked against robust datasets (4, 15). As a consequence, some NbCS projects have already failed to deliver the tangible climate benefits they were intended to provide (6, 7, 16).

Ambitious NbCS programs could deliver benefits for biodiversity, communities, and the climate. Unfortunately, a lack of evidence about specific benefits from specific strategies prevents researchers and policymakers from confidently prescribing when and where they should be used.

Fortunately, the recent surge in federal and private-sector spending on NbCS projects offers the United States the chance to develop the research infrastructure necessary to create robust and credible programs. While many of the new federal initiatives are designed to foster NbCS implementation, they also direct substantial resources toward research on NbCS effectiveness. Importantly, in July 2023, the White House released a draft "federal strategy" (17) to develop a coordinated approach for measuring, monitoring, reporting, and verifying (MMRV) land-sector GHG exchanges, with a particular emphasis on generating the data needed to evaluate NbCS. This strategy was then incorporated into a broader "National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System," which was released in November 2023 (18). Many aspects of this new framework, including a new soil carbon monitoring network and more robust tracking of changes in forest biomass, are long overdue and represent important steps toward more robust and credible NbCS programs.

But the strategy can still be improved. In particular, we argue that it should establish a hierarchical system of networks that leverages the best available scientific tools, be applicable across a broad range of spatial scales, and rest on a bedrock commitment to free and open data sharing.

Open Data and Code

Data and products generated by federal agencies or through external partnerships should be openly and freely accessible to all interested parties, including nonfederal scientists, state and local government officials, and cultural and natural resource managers. Open and accessible databases are critical to drive science forward and develop next-generation approaches for MMRV. This emphasis on transparency, which aligns with the White House's 2023 "Year of Open Science" initiative, should also extend to the protocols used to monitor and verify NbCS projects. Right now, these protocols vary substantially (14, 15) and lack rigorous standardization against common datasets (4), which limits the system-wide equivalency of carbon credits and erodes confidence in NbCS implementation (6, 7, 15). The "Greenhouse Gas Center" that was created as part of phase 1 of the strategy could be a useful platform for open data and code sharing. Realizing this promise will require communication and collaboration across all pertinent federal agencies and nonfederal stakeholders. Only then can we ensure that the right data are ingested in the right formats.

Data from federal monitoring networks should also be shared in transparent formats that allow ground observations to be directly compared with information from high-resolution remote sensing imagery. For existing USDA programs like the FIA, sharing the precise location of data collected on private lands is actually prohibited by federal law. As a result, in order to protect landowner privacy, the USDA obscures the plot locations by adding noise to the data. Open databases should, indeed, adhere to best practices for data privacy and sovereignty, especially when collected on private and Indigenous lands. However, the USDA applies this same protocol to data collected on public lands, where privacy laws do not apply. The rationale for this policy is to preserve the long-term integrity of the field plots (19), an important imperative. However, alternatives should now be considered. We can achieve a broader public good by creating pathways for scientists to verify carbon budgets and improve monitoring approaches that draw upon high-resolution satellite data. Opening up the true coordinates on public lands to researchers would be a strong step in that direction.

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A Hierarchical Network of Networks

Most approaches for evaluating and monitoring NbCS focus on the change in carbon in shallow soil layers and in above-ground tree biomass (with additional accounting for emissions of non-CO_2 GHGs in some agricultural settings). While these two pools are among the most dynamic reservoirs for ecosystem carbon, this approach does not adequately sample other important carbon pools, including deep soil layers, forest soils, litter, and coarse-woody debris (4, 20). Existing, pool-centric accounting also cannot tell us much about how NbCS impact surface albedo and net cooling (21). Also, in forests, a pool-based accounting approach relies on empirical equations based on data from trees harvested decades ago, which do not reflect the more recent combined effects of multiple climate feedbacks. Finally, since ecosystem carbon pools are often large, it can take several years for a change in these pools to become detectable (4).

We should adopt a more robust approach that uses a hierarchy of measurements over a range of spatial and temporal scales (4, 8). Networks of eddy covariance flux towers, such as AmeriFlux and the NSF's National Ecological Observatory Network, already provide continuous, long-term, ecosystem-scale data on CO_2 and energy fluxes for hundreds of locations in the United States. Many also provide long-term data on ecosystem-scale CH_4 and N_2O fluxes (8). Ecosystem-scale data from these flux towers can be compared to bottom-up estimates from soil and biomass inventories (especially when carbon losses from harvest or runoff are small or accounted for) and to high-resolution, multidimensional satellite data. Flux towers should be incorporated into the design of federal GHG monitoring networks, especially in areas of relatively flat and homogeneous terrain, where towers work best. This would create gold-standard datasets, where carbon fluxes and pools can be carefully monitored together with environmental drivers and near-surface remote sensing (4).

Locating new soil carbon and FIA monitoring network plots near flux towers is one way to generate such gold-standard datasets. It would also engage ecologists in this critical work to evaluate the strengths and biases of NbCS monitoring approaches. And such a hierarchical network design would also help to shed light on the mechanisms of claimed NbCS schemes, to evaluate and certify verification protocols, and to benchmark remote-sensing mapping tools and predictive models. A wealth of pre-existing and planned research infrastructure provides a solid foundation for creating this hierarchical network (4). However, realizing this vision requires strategic coordination among federal and nonfederal researchers.

Mapping Land Cover and Use

Researchers need large-area maps of land cover and use, disturbances, and management activities in order to monitor the baseline management regimes, to attribute carbon outcomes to management and disturbance shifts, and to extrapolate from point-based monitoring networks to broader assessments at policy-relevant scales. Here, the federal strategy's focus on improving the accessibility and resolution of data on the distribution of NbCS-relevant management practices is encouraging. The collection of management-activity data from working lands would be especially valuable if it were coordinated with the collection and open sharing of soil carbon and GHG outcomes (such as from the new soil carbon monitoring network).

Still, the carbon-cycle consequences of disturbance- and management-driven shifts are major unknowns that prevent robust estimates of additionality and durability (5). In forests, attributing these impacts requires accurate, low-latency monitoring of disturbance events and their proximal causes (such as wildfires, insect outbreaks, and drought-driven die-offs), coupled with strategic monitoring of the postdisturbance consequences for carbon pools and fluxes.

To achieve this, we should better integrate aerial survey data from the USDA Forest Health Monitoring program with the permanent sampling plot network of the FIA and satellite remote sensing. This would be especially useful when guided by machine-learning approaches for aerial image processing. Consistent, national-scale maps and databases that document historic management activities are urgently needed. Finally, cost-effective opportunities exist to enhance the temporal resolution of forest inventory programs such as the FIA by collecting tree-ring data (22) to fill temporal gaps between plot survey intervals. Combined, these steps would improve and even re-imagine the modeling tools available to estimate forest carbon storage from regional scales down to the scale of individual forest NbCS projects. Achieving these goals will likely require resources for federal programs that generate ground and space-borne data on land use, management, and disturbance, as well as federal and private investment in projects directed by both federal and nonfederal researchers that leverage the raw data into policy-relevant products.

Building a solid scientific basis for NbCS on a timeline that corresponds with their implementation will not be easy.

Building a solid scientific basis for NbCS on a timeline that corresponds with their implementation will not be easy. But by prioritizing and focusing on the three principles we outline above, the US research community can leverage existing carbon-cycle science research tools and networks to rapidly generate the information necessary to support robust NbCS programs. The scale of coordination and investment required to develop such a framework is sizable. Nonetheless, it is within the scope of the planned federal investment and would cost substantially less than the tens of billions of dollars recently allocated for implementation of NbCS projects with uncertain outcomes. This investment is the best way to reduce the significant risks of controversial implementation failures, while at the same time build public confidence in nature-based solutions to climate change.

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Author affiliations: [a]O'Neill School of Public and Environmental Affairs, Indiana University, Bloomington, IN 47405; [b]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720; [c]Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; [d]Wilkes Center for Climate Science and Policy, University of Utah, Salt Lake City, UT 84112; [e]School of Biological Sciences, University of Utah, Salt Lake City, UT 84112; [f]Bipartisan Policy Center, Washington, DC 20005; [g]Department of Biological & Agricultural Engineering, University of Arkansas, Fayetteville, AR 72701; [h]Environmental Defense Fund, Washington, DC 20077; [i]Carboneers, Oakton, VA 22124; [j]Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721; [k]Department of Earth System Science, University of California, Irvine, CA 92697; [l]Woodwell Climate Research Center, Falmouth, MA 02540; [m]Energy and Resources Group, University of California, Berkeley, CA 94720; [n]Department of Geography University of California, Santa Barbara, CA 93106; and [o]Graduate School of Geography, Clark University, Worcester, MA 01610

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