The science needed for robust, scalable, and credible nature-based climate solutions for the United States: Full Report

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2022-10-12

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This report emerged from a workshop in Washington, DC, June 28-29th, 2022. Workshop funding and programmatic support came from the Department of Energy's AmeriFlux Management Project, Indiana University's O'Neill School of Public and Environmental Affairs, and the US Carbon Cycle Science Program.

The views expressed in this report do not necessarily reflect the views of individual contributing authors or their respective institutions.

Acknowledgements: The report authors are grateful for the support provided by the Indiana University O'Neill School of Public and Environmental Affairs (Indiana University - Bloomington), the AmeriFlux Management Project, and the U.S. Carbon Cycle Science Program for supporting the workshop and the writing process. We especially acknowledge Katherine Devich and Nikki Rolf Boyd for logistical support during the workshop, and Christin Buechner for programmatic support leading up to the event. Jeff Atkins, Connor Nolan, Rachel Oidtman, Ann Raiho, and Haley Ritger are gratefully acknowledged for the feedback on an earlier version of the report. We are indebted to the full set of workshop participants for their constructive discussions and engagement, and we acknowledge other members of the AmeriFlux Natural Climate Solutions working group for a series of conversations over the past two years that provided the genesis for this workshop and paper. We are grateful for the creative contributions of William Scavone (Kestrel Studio - kestrelstudio.com), Mike Jackson, and Sean Miller to the report's graphics and formatting.

Recommended Citation: Novick, K. et al. The science needed for robust, scalable, and credible nature-based climate solutions in the United States: Full Report. (2022)

1 Overview and Objectives

1.1 Growing support for terrestrial Nature-based Climate Solutions in the United States

The impacts of climate change are accelerating non-linearly with devastating consequences, and mitigating the problem is fundamental for the national interest and societal well-being. More frequent and intense wildfires, droughts, floods, and heatwaves are already posing grave and interconnected threats to agriculture, human health, biodiversity, and physical infrastructure(Walker et al. 2019; Novick et al. 2022). The scientific consensus on how to reverse the course of climate change is clear – we need to dramatically reduce, and eventually eliminate, anthropogenic emissions of greenhouse gases from fossil fuel burning, other industrial processes, and land management practices. However, given the relatively slow pace of mitigation to date, emissions reductions alone will likely be insufficient to prevent dangerously high levels of warming6, and they will need to be complemented by approaches for removing CO2 directly from the atmosphere.

Land-based carbon removal strategies which harness naturally occurring ecosystem processes have a particularly broad base of support7,8. **These Nature-based Climate Solutions (NbCS9,10) are not a panacea for reversing climate change and can only be effective when pursued concurrently with economy-wide decarbonization11.** Nonetheless, NbCS are part of nearly all net-zero pathways12, reflecting the crucial role of terrestrial ecosystems in driving the global carbon cycle. The terrestrial biosphere absorbs roughly 15% of the carbon in the atmosphere each year through photosynthesis, but then returns a nearly equal amount through respiration13-15. These large photosynthesis and respiration fluxes approach a long-term balance under steady atmospheric and climatic conditions. However, since the Industrial Revolution, the biosphere has been out of equilibrium. Rising atmospheric CO2 and increased nitrogen deposition are increasing photosynthesis more than respiration, such that the rate of net carbon uptake on land has increased over the past century, and even doubled since the 1960s16,17. As a result, **terrestrial ecosystems currently absorb 25% to 33% of the CO2 emitted annually by human activities15.** Important questions remain concerning the cause of this imbalance and the fate of the land carbon sink in a warmer world that will face increasing and competing land use pressures16,18,19. Nonetheless, right now, terrestrial ecosystems undeniably sequester and store a large fraction of anthropogenic emissions of CO2, substantially slowing the pace of climate change.

Collectively, NbCS represent management approaches and technologies designed to increase net carbon uptake and/or reduce “natural” emissions of methane (CH4), ozone (O3), and nitrous oxide (N2O), which are powerful non-CO2 greenhouse gasses (hereafter GHGs). In general, land based NbCS can be classified into management approaches applicable to forested ecosystems, croplands and grasslands, and terrestrial wetland ecosystems:

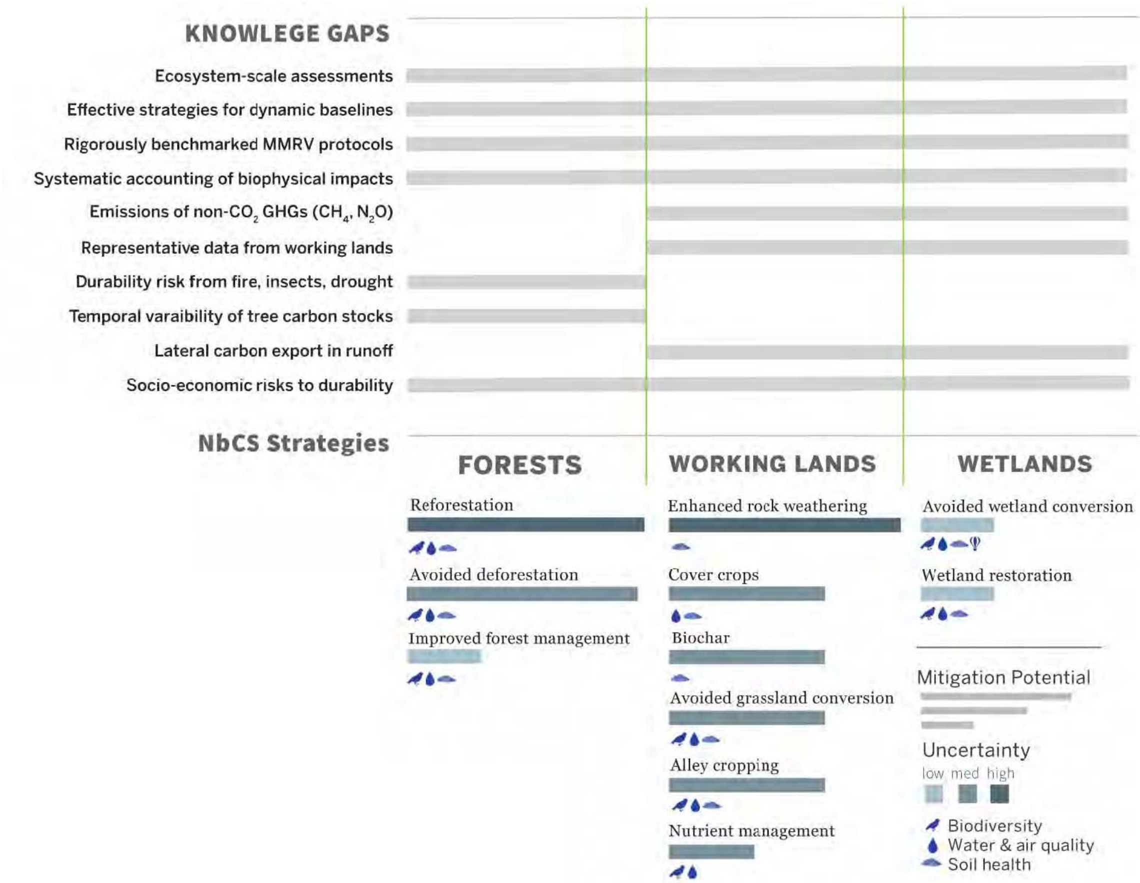
- **Forest NbCS:** The carbon sequestration capacity of forests is large and well-established. The United States is home to 8% of the world’s forest land (FAO 2020), ranking 4th of all countries in terms of forested area. Long before climate change was a central research theme, ecologists developed theories to explain how carbon uptake varied as forests recovered from harvest and other disturbances20. They hypothesized that regenerating forests would offset disturbanceinduced carbon emissions by functioning as carbon sinks for decades before the balance between photosynthesis and respiration diminished. Since then, modern measurement approaches have largely confirmed the hypothesis – even mature, 100-year-old forests function as strong carbon sinks in many parts of the country21-24, often sequestering and storing 2-6 Mg C/ha/yr22. By one estimate, forests of the Eastern U.S. sequester an amount of CO2 equivalent to 40-60% of emissions from fossil fuel burning in the same region25. At the continental scale, North American forests are estimated to sequester carbon at a rate equal to about 12% of the continent’s fossil fuel emissions26,27. Moreover, across much of the United States, the current distribution of forest cover is quite low when compared to pre-colonization baselines, owing to a legacy of widespread forest clearing in the 18th and 19th centuries28. Thus, it is not surprising that reforestation – the regeneration of forests in places where they previously existed - is the NbCS believed to have the highest overall mitigation potential, followed closely by altered forest management strategies such as longer intervals between timber harvests29. However, in parts of the United States prone to forest disturbance from fire, insects, drought, and logging (which includes most of the western U.S.30,31), the durability of carbon stored in forest ecosystems is not at all assured.

- **Cropland and grassland NbCS:** In croplands and grasslands that are dominated by annual plants, the primary longterm sink for atmospheric carbon resides in the soil. There is general agreement that a large proportion of agricultural soils have lost soil organic carbon (SOC), with an estimated global loss of 31 Pg of carbon (from the top 30 cm) due to anthropogenic land use changes over the last 12,000 years32. A large body of research has shown that agricultural practices that reduce soil disturbance, increase the amount of organic inputs to the soil, and maintain continuous plant cover can restore or enhance some of the lost SOC in surface soils33-38. These include planting cover crops during fallow periods when cropland soil is otherwise bare, avoiding grassland conversions, reducing tillage, and a growing set of strategies (e.g., biochar addition, enhanced mineral weathering) designed to increase the soils’ capacity for long-term carbon storage. This sector also offers opportunities for reduced nitrous emissions through fertilizer management and reduced methane emissions through changes in manure handling and rice and ruminant production systems.

- **Terrestrial Wetland NbCS:** Wetlands in the conterminous United States store ~12 Pg carbon, with significantly more carbon stocks in undisturbed than disturbed sites39. Wetlands offer many opportunities for enhancing ecosystem services, including both carbon storage and GHG emission reductions. There are two main categories of NbCS for wetlands: wetland restoration and avoided conversion of wetlands40,41. The climate impact of these strategies depends on balancing carbon storage (achieved in part through waterlogging) and methane emissions (resulting from waterlogged conditions) among other landscape objectives42,43. Achieving this balance may delay some of the cumulative GHG benefits of restored wetlands for decades or longer44.
- **Hybrid Approaches:** With hybrid approaches, standing carbon stocks are harvested and stored for the long-term while allowing post-harvest recovery of those carbon stocks to remove carbon from the atmosphere. Carbon stored in long-lived harvested wood products (order 100 years) is one example. "Wood vaults45", the direct burial of harvested wood in anoxic conditions, is a less familiar approach. By storing carbon in more recalcitrant forms or changing the storage conditions to reduce decomposition, hybrid solutions could potentially dramatically increase the durability of carbon storage and reduce the risk of loss. Removing biomass for processing also allows for simplified monitoring and measurement. However, studies confirming the benefits of hybrid carbon cycle approaches like these are scarce.

Unlike other strategies for removing CO2 from the atmosphere (e.g., direct air capture), most NbCS are associated with well-known co-benefits for biodiversity, air and water quality, and/or soil health10,29,40. NbCS interventions can also produce pronounced impacts on local temperature and water regimes in addition to their impact on carbon uptake and GHG emissions46,47. These impacts may not always counteract the effects of climate change48,49, but when and where they do, they present farmers, foresters, Indigenous peoples, and other land stewards with novel tools to increase the resilience of their lands to future climate change50. NbCS on working lands may represent especially low hanging fruit, since agricultural lands are already intensively managed. Some NbCS also have favorable economic benefits for landowners and could be implemented at a relatively low cost when compared with other negative emissions technologies. However, cost comparisons among carbon removal strategies are only valid if the approaches are similarly effective and provide long-lasting climate benefits over comparable timescales51.

Right now, NbCS strategies have strong and growing support from a unique coalition of actors, including bipartisan lawmakers, conservation groups, the private sector, and many federal and state agencies. At the national level, NbCS feature prominently in the Bipartisan Infrastructure Law (IIJA), Inflation Reduction Act (IRA) and Executive Order 14072, and are being rigorously evaluated by NGOs and think tanks29,50,52-55 as well as broad consortia of university and public sector scientists7-9,56-58. At more local scales, cap-and-trade policies administered by California's Air Resources Board and the Regional Greenhouse Gas Initiative have fueled compliance carbon market activity amounting to millions of credits valued at billions of dollars52. In the private sector, the NbCS landscape is dynamic and evolving quickly. Voluntary carbon markets have experienced significant growth in the last 2-3 years, trading ~$1 billion in offsets in 202159,60. Strategies for monitoring, reporting, and verifying carbon offsets within voluntary market systems are evolving61 and many private sector actors are considering next-generation strategies for incentivizing NbCS that do not rely on offsets62. The rapid proliferation of public and private sector NbCS initiatives gives every indication that NbCS will be a core feature of domestic climate mitigation strategies moving forward.



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Key criteria, limitations, and opportunities While there is ample justification for implementing NbCS based on their co-benefits alone, for NbCS to succeed specifically as climate mitigation tools, they must meet four essential criteria:

- Criteria 1: Lead to enhancements to carbon uptake and/or reductions of non-CO2 GHGs that are additional to what would have occurred in a baseline or counterfactual scenario, and that integrate over all ecosystem sources and sinks.
- Criteria 2: Lead to net cooling such that the biophysical effects on water and energy cycling do not overwhelm the gains in carbon uptake or emissions reductions.

- Criteria 3: Achieve durable carbon storage by accounting for social and environmental risks to the permanence of ecosystem carbon storage and avoided GHG emissions.
- Criteria 4: Account for leakage so that gains in one area are not canceled out by shifting activities to another area.

As discussed in detail in this report and elsewhere, major knowledge gaps and concerns surrounding current NbCS activities and protocols limit the extent to which they fulfill these criteria8,10,30,52,63,64 (Fig. 1). At regional and continental scales most relevant to policy-setting, estimates of the present-day mitigation potentials of NbCS vary substantially from one study to the next.2-4 These potentials are usually estimated as a change in the amount of carbon residing in two slowly evolving carbon stocks: shallow soil and aboveground plant biomass. A focus on these two pools alone cannot capture the ecosystem-scale carbon impacts of NbCS and tells us little about emissions of non-CO2 GHGs (criteria 1). Moreover, for many NbCS, existing data on how these stocks change are sparse and unrepresentative of naturally occurring environmental gradients, limiting the available information necessary to inform baselines against which additionality can be calculated (criteria 1). A focus on changes in carbon stocks also does not capture "biophysical" impacts of NbCS that can have both favorable and unintended direct effects on temperature and water cycling (criteria 2). Furthermore, the durability of carbon stored in soils and woody biomass (criteria 3), as well as the leakage potential (criteria 4) are difficult to quantify and are not robustly considered in NbCS accounting schemes. Together, these uncertainties reveal critical challenges that hinder quantification of NbCS impacts from local to continental scales, now and into the future.

Fortunately, substantial opportunity exists to address this uncertainty by harnessing state-of-the-art carbon cycle measurement and prediction tools together with lessons learned from practical experience in implementing NbCS on the ground. The dominant role of terrestrial ecosystems in determining atmospheric CO2 concentrations has been known for decades. Consequently, huge investments of material resources have fostered the development of innovative measurement technologies, analytical tools, and predictive models for quantifying ecosystem carbon cycles (Fig. 2). By and large, these tools have historically been used for basic research of ecological processes and to inform global-scale predictions for the future land carbon sink; but so far, the vast majority have not been widely leveraged for what they might tell us about expected and realized benefits of NbCS. Likewise, novel approaches for crediting and verifying the climate benefits of NbCS are proliferating at a range of scales, though most have not yet been widely deployed61,62. Thus, right now, as we face a sea change in federal and private-sector engagement with NbCS, we have a unique opportunity to integrate the best-available science into next-generation information systems to support effective NbCS programs and policy that address all four key criteria.

i Box 1: Elements of robust, scalable, and credible NbCS

- **Robust:** NbCS incentivization programs fully address all four key criteria (additional mitigation, net cooling, durability, and leakage). Doing so means that NbCS accounting schemes

1. are informed by ecosystem-scale data that integrate over all carbon sources and sinks,
2. consider a full set of GHG fluxes,
3. explicitly account for the durability of carbon stored in soils and tree biomass and the possibility of leakage, and
4. are holistic, considering not only the climate mitigation potential, but also coupled biophysical impacts on energy and water cycling.

- **Scalable:** The strategies used to quantify the benefits of individual NbCS projects are harmonized with approaches to map the same benefits over regional and continental scales, so that NbCS programs can be informed by an understanding of when and where specific strategies are most likely to succeed.
- **Credible:** The policy instruments used to incentivize NbCS rely on monitoring and quantification tools that are rigorously standardized and cross-compared, with open and transparent data and code sharing, allowing for independent validation of all activities and projections.

1.2 A path forward

The objective of this report, which is co-authored by experts in both NbCS science and implementation, is to describe the technologies, tools and approaches necessary to support robust, scalable, and credible NbCS strategies for the US. The report is organized around the identification of key knowledge gaps and pathways to close them, providing a road map for actionable, cross-sectoral information to foster NbCS strategies that work while avoiding energy wasted on NbCS strategies that have limited environmental benefits or the potential to backfire and exacerbate climate change. The criteria for robust, scalable, and credible NbCS defined in Box 1.

Before we proceed, there are two things to keep in mind. First, it is important to distinguish between the concepts of "technical mitigation potential" and "realizable mitigation potential," which is sometimes also referred to as "social potential" or "economic potential." Technical mitigation potential describes increases in carbon uptake and/or reductions in GHGs emissions that are theoretically achievable through NbCS interventions, usually determined per unit area and summed across all available areas. The factors that influence the technical potential include heterogeneity in biophysical factors like climate, species composition, and nutrient cycles, as well as uncertainties in our ability to accurately measure changes in fluxes of CO2 and other GHGs. The realizable mitigation potential includes other factors, such as the sociological and economic forces that determine landowner willingness to adopt or sustain a "climate-smart" practice. This report is most strongly focused on research needed to quantify and predict the technical mitigation potential of NbCS. Frequently, gaps and research needs related to the realizable potential are also highlighted.

Second, the knowledge gaps that we identify in Section 2 are not trivial and appear to reveal a wide gulf between the state-of-the-science surrounding NbCS and the pace at which NbCS strategies are being implemented on the ground. Indeed, there are many points of disconnect, including a lack of consensus among scientists about the realizable climate benefits of these strategies56, a dearth of representative data necessary for more confident quantification of NbCS impacts, and the fact that many protocols used for most NbCS project accounting were developed decades ago and do not leverage the best-available science. However, it is important to remember that terrestrial ecosystem ecology is a well-established field of study, and over the decades, we have gained a tremendous amount of knowledge about the mechanisms that drive variability in ecosystem carbon, water, energy, and nutrient cycles. Critically, we have also developed a wide variety of pre-existing experimental sites, datasets, technologies, and analytical tools that have not yet been fully leveraged for what they reveal about NbCS (see Section 3). Thus, relatively subtle shifts in the research questions we ask and the scale at which we ask them, combined with strategic expansion of existing field sites and monitoring networks, could substantially alleviate the burden of material resource investment necessary to address these knowledge gaps (see details in Section 4).

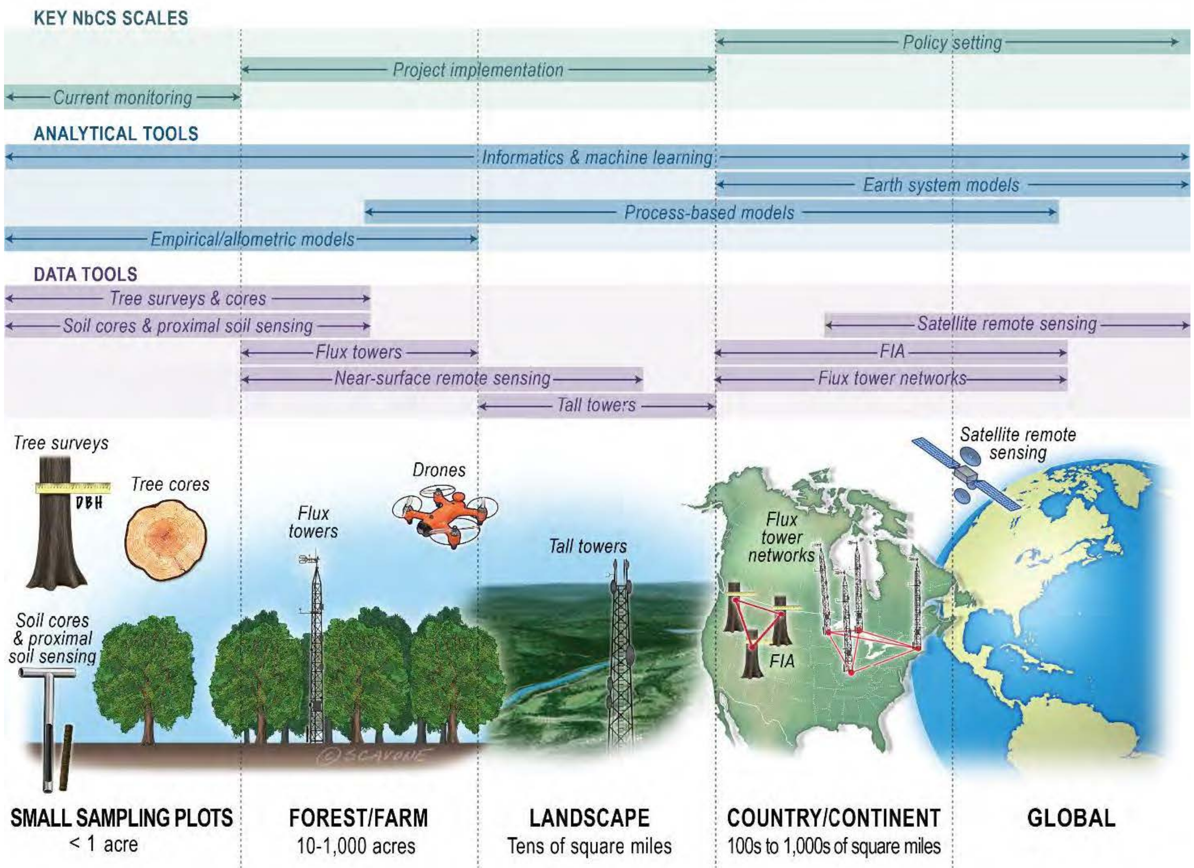

Figure 1.1: The data and analytical tools that could be more fully leveraged to inform NbCS. See Section 3 for details. Image copyright William Scavone. All rights reserved.

2 Knowledge Gaps Limiting Robust, Scalable and Credible NbCS for the United States

2.1 Knowledge gaps related to field data scarcity

Our understanding of the technical mitigation potential of many NbCS strategies is limited by a scarcity of representative field data, either because these data do not yet exist or because they are not yet freely accessible. Notable exceptions exist, including networks of ecosystem-scale flux towers (e.g., AmeriFlux65,66 and NSF's National Ecological Observatory Network, or NEON67) and the wealth of information on tree biomass and associated stand dynamics supported by the USDA Forest Service Forest Inventory and Analysis (FIA) program68. These networks may provide sufficiently representative data to map carbon fluxes at coarse scales69, or even to estimate potential changes in plant carbon stocks achievable with some NbCS like reforestation70,71. However, networks like NEON, FIA and AmeriFlux were not designed specifically with the goal of evaluating NbCS, and many specific NbCS management strategies (e.g., cover crops, soil amendments, altered forest management, wetland restoration) are potentially un- or under-represented in these networks. These networks were also not designed to be interoperable, which makes it difficult to blend information from disparate networks (e.g., FIA and AmeriFlux) into synthetic analyses and products. Efforts to dynamically catalog existing NbCS field trials and the activities of relevant monitoring networks would permit an informed prioritization of new data collection and facilitate synthesis of new and existing network data.

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