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

Full Report

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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[1-5]. 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 warming[6], and they will need to be complemented by approaches for removing CO_2 directly from the atmosphere.

Land-based carbon removal strategies which harness naturally occurring ecosystem processes have a particularly broad base of support[7,8]. **These Nature-based Climate Solutions (NbCS[9,10]) are not a panacea for reversing climate change and can only be effective when pursued concurrently with economy-wide decarbonization[11].** Nonetheless, NbCS are part of nearly all net-zero pathways[12], 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 respiration[13-15]. 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 CO_2 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 1960s[16,17]. As a result, **terrestrial ecosystems currently absorb 25% to 33% of the CO_2 emitted annually by human activities[15]**. 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 pressures[16,18,19]. Nonetheless, right now, terrestrial ecosystems undeniably sequester and store a large fraction of anthropogenic emissions of CO_2, 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 (CH_4), ozone (O_3), and nitrous oxide (N_2O), which are powerful non-CO_2 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 disturbances[20]. They hypothesized that regenerating forests would offset disturbance-induced 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 country[21-24], often sequestering and storing 2-6 Mg C/ha/yr[22]. By one estimate, forests of the Eastern U.S. sequester an amount of CO_2 equivalent to 40-60% of emissions from fossil fuel burning in the same region[25]. 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 emissions[26,27]. 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 centuries[28]. 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 harvests[29]. 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 long-term 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 years[32]. 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 soils[33-38]. 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 sites[39]. 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 wetlands[40,41]. The climate impact of these strategies depends on balancing carbon storage (achieved in part through waterlogging) and methane emissions (resulting from water-logged conditions) among other landscape objectives[42,43]. Achieving this balance may delay some of the cumulative GHG benefits of restored wetlands for decades or longer[44].

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 vaults[45]", 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 CO_2 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 health[10,29,40]**. NbCS interventions can also produce pronounced impacts on local temperature and water regimes in addition to their impact on carbon uptake and GHG emissions[46,47]. These impacts may not always counteract the effects of climate change[48,49], 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 change[50]. 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 timescales[51].

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 tanks[29,50,52-55] as well as broad consortia of university and public sector scientists[7-9,56-58]. 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 dollars[52]. 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 2021[59,60]. Strategies for monitoring, reporting, and verifying carbon offsets within voluntary market systems are evolving[61] and many private sector actors are considering next-generation strategies for incentivizing NbCS that do not rely on offsets[62]. **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.**

KNOWLEDGE GAPS

- Ecosystem-scale assessments
- Effective strategies for dynamic baselines
- Rigorously benchmarked MMRV protocols
- Systematic accounting of biophysical impacts
- Emissions of non-CO_2 GHGs (CH_4, N_2O)
- Representative data from working lands
- Durability risk from fire, insects, drought
- Temporal variability of tree carbon stocks
- Lateral carbon export in runoff
- Socio-economic risks to durability

NbCS Strategies

FORESTS
- Reforestation
- Avoided deforestation
- Improved forest management

WORKING LANDS
- Enhanced rock weathering
- Cover crops
- Biochar
- Avoided grassland conversion
- Alley cropping
- Nutrient management

WETLANDS
- Avoided wetland conversion
- Wetland restoration

Mitigation Potential

Uncertainty
low med high

Biodiversity
Water & air quality
Soil health

Fig. 1: Terrestrial Nature-based Climate Solutions in the United States. In the bottom of the figure, the length of the bar indicates (qualitatively) the expected carbon mitigation potential, and the color represents uncertainty around this potential. Icons indicating relevant co-benefits. Based largely on information presented in Farigone et al. 2018[29]. The top of the figure highlights some of the most pressing knowledge gaps (see Section 2 for more detail).

1.2 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: A**ccount 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 criteria[8,10,30,52,63,64] (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-CO_2 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 CO_2 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 deployed[61,62]. **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.**

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.

1.3 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 CO_2 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 strategies[56], 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).
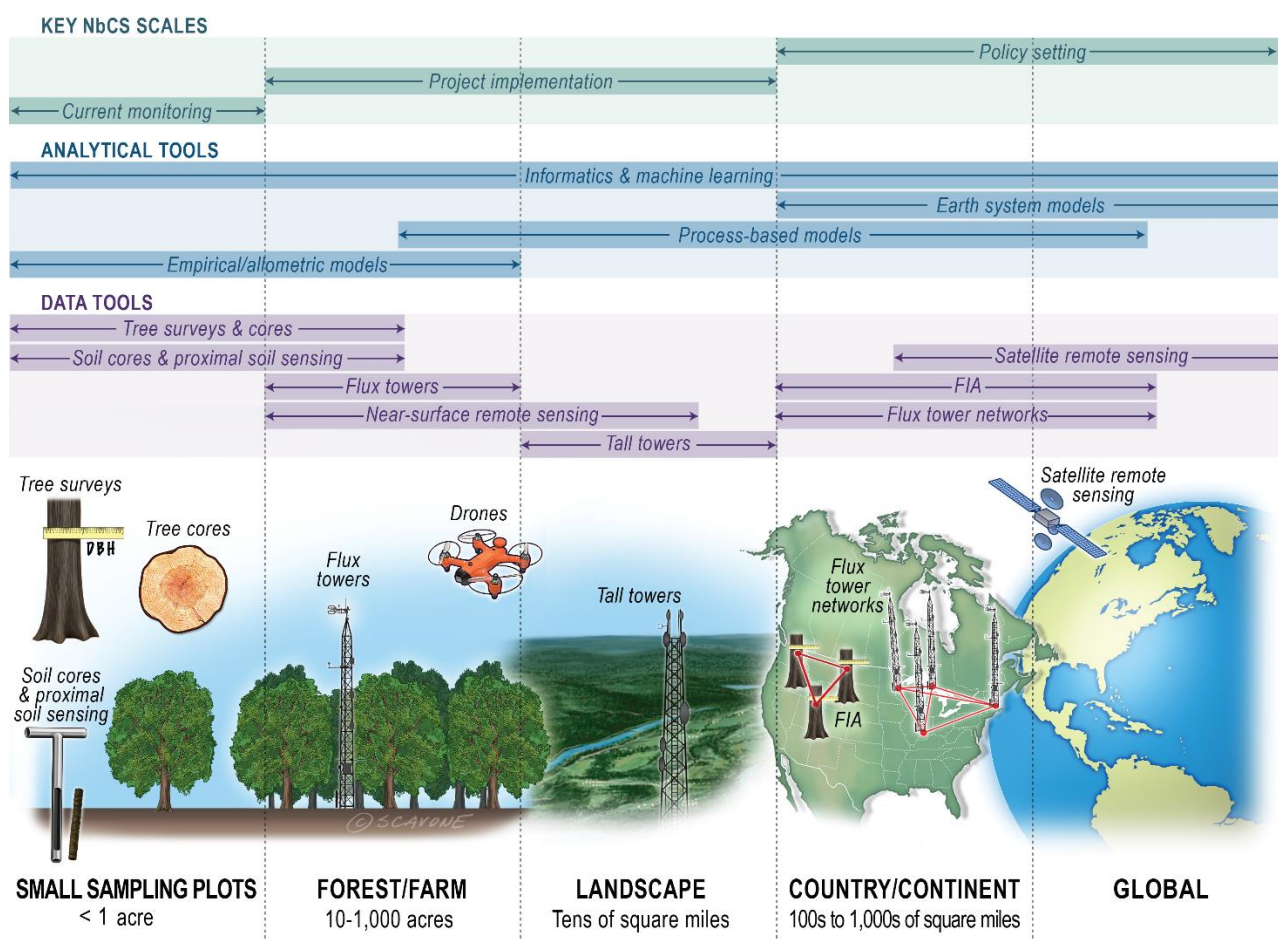

Figure 2: The data and analytical tools that could be more fully leveraged to inform NbCS. See Section 3 for details. Image copyright William Scavone. All rights reserved.

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., AmeriFlux[65,66] and NSF's National Ecological Observatory Network, or NEON[67]) and the wealth of information on tree biomass and associated stand dynamics supported by the USDA Forest Service Forest Inventory and Analysis (FIA) program[68]. These networks may provide sufficiently representative data to map carbon fluxes at coarse scales[69], or even to estimate potential changes in plant carbon stocks achievable with some NbCS like reforestation[70,71]. 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.

Particularly in agricultural systems, there is a lack of scientific consensus about the degree to which NbCS practices can sequester sufficient atmospheric carbon to help mitigate climate change[72-75]. This disagreement stems in part from a **large degree of uncertainty surrounding the spatial and temporal patterns of soil organic carbon (SOC) and net GHGs across agricultural landscapes[76-80].** Field trials for emerging NbCS strategies (e.g., enhanced rock weathering) are scarce. However, there is even a lack of representative soil carbon storage data for a practice like cover cropping, which has long been known to confer multiple environmental benefits for soil health and water quality[81-83]. One of the most widely cited papers reporting on the soil carbon benefits of cover crops[34] is informed by data from 37 sites globally, with only 10 locations within the United States. Likewise, although no-till management has long been lauded for its benefits to soil health and for its role in reducing on-farm fossil fuel emissions, the ability of no-till management to sequester atmospheric carbon has been hotly debated in the scientific literature[72,84]. Some studies conclude it has no potential to mitigate climate change, whereas other research suggests that mitigation potential depends on climate and soil texture[85]. Almost no data exists on the impact of multiple, or stacked, NbCS farming practices despite the widespread use of stacking among regenerative farmers. **More data is needed from a much more representative set of ecosystems** to quantify where these practices succeed as climate solutions, alone and in combination.

The mechanisms by which agricultural practices impact coupled carbon and nitrogen dynamics is another major knowledge gap. Understanding the net GHG impact of agricultural management demands data on how specific practices impact both soil organic carbon (SOC) and associated GHGs like nitrous oxide and methane. Agricultural practices that build SOC can result in increased nitrous oxide emissions, which could potentially offset gains in SOC sequestration[86,87]. Quantifying potential trade-offs is difficult because nitrous oxide emissions vary temporally and spatially and constitute a highly uncertain component of agricultural GHG budgets[87]. In addition, practices which may reduce N_2O from fertilizer or manure application may adversely affect other parts of the nitrogen cycle and increase ammonia loss[88]. **We need increased data coverage over time and space to more accurately quantify the net GHG impacts and additional positive or negative effects of agricultural management practices.** These databases could build onto and complement USDA Agricultural Research Service GHG synthesis projects such as TRAGNET[89] and GRACEnet[90,91].

Our understanding of NbCS potentials in agricultural landscapes moreover **requires data from <u>working farms</u>**. Much of our knowledge about management impacts on SOC sequestration comes from long-term agricultural field trials designed to minimize inherent variability in soils and landscape position that exists in the real-world[92]. Thus, estimates of SOC sequestration rates are often greater than those measured at the farm scale[93], and practices as implemented in

research trials (e.g., long-term no-tillage) might not reflect how these practices are implemented in practice by farmers (e.g., intermittent tillage). A network of sites (ideally containing paired fields evaluating different practices) that collect data on management records, soil properties, climate data, crop yields, carbon fluxes, and nitrogen fluxes could help build external validity of agricultural management impacts on net GHG outcomes.

Many of these field data limitations also apply to terrestrial wetland ecosystems, which have additional, unique knowledge gaps. There is still a need to better map wetlands[94] and to locate restoration and conversion avoidance opportunities more precisely. Next, **emissions and carbon trajectories associated with different wetland conditions and restoration strategies need to be rigorously quantified**. The use of eddy covariance combined with long-term, plot-level measurements of GHG emissions are important tools to fill this gap[95], though wetlands are relatively underrepresented in networks like AmeriFlux and NEON[96]. Wetlands also pose measurement difficulties as they are a mosaic of water and vegetation with stark gradients in nutrients, plant species, soil saturation and salinity (for estuaries) that can impact carbon cycling and GHG emissions[97-99]. Getting the fluxes right at the field-scale requires a mix of measurement and gap-filling approaches and high-resolution remote sensing[100,101]. It is also important to consider socioeconomic factors, including the design of locally appropriate incentive programs that account for competing land uses and the multiple ecosystem services[102,103], plus impacts associated with disturbance[104].

Especially in wetland environments and the tile-drained croplands that predominate the Corn Belt, **more information is required regarding potentially significant leakage through lateral transport of dissolved and particulate carbon[105-107]**. A change in SOC may represent an increase in carbon sequestration from the atmosphere, but it may also represent a decrease in carbon losses through runoff and leaching. Depending on the fate of carbon exported in this way, an increase in soil carbon may not represent atmospheric CO_2 sequestration of the same magnitude. Unfortunately, information about lateral export of carbon, especially in places where carbon pools and fluxes are already being measured, is scarce and largely unaggregated into network databases.

Field data on the carbon contained in forests are relatively more plentiful, due in large part to the FIA program. Indeed, FIA data have played a central role in governing our understanding of the dynamics of carbon stored in tree biomass, and FIA biomass data are featured in most attempts to quantify the mitigation potential of reforestation in the U.S.[31,70,108-110]. However, FIA was not designed explicitly for the purpose of documenting how a limited set of management strategies will alter the GHG flux balance of America's forests. For example, while SOC has been measured on a subset of FIA plots[111], **data on changes in soil carbon are not yet available from FIA**. Moreover, the FIA network is characterized by **long resampling intervals** (5-10 years) and protocols that **lack rigorous documentation of the causes of tree mortality or regeneration of young trees.** These limitations make it difficult to disentangle the influence of multiple drivers of forest carbon dynamics that act simultaneously, including climate variability and change, natural disturbances, forest harvest, the CO_2 fertilization effect, and their interactions. Furthermore, **whether distributed plot networks like FIA adequately capture the carbon cycle impacts of patchy disturbances, particularly fire and beetle outbreaks, is also a major unknown**.

Box 2.1: Knowledge gaps related to data scarcity

Gap 2.1a: Many categories of NbCS are under-represented in existing networks, and field trial data are scarce.

Gap 2.1b: The absence of long-term monitoring data on soil carbon in agricultural working lands limits consensus on when and where many NbCS are most likely to succeed.

Gap 2.1c: Unrepresentative data on coupled soil carbon and nitrogen dynamics, and lateral carbon transport, limits evaluation of inherent tradeoffs (e.g. carbon versus methane and nitrous oxide, sequestration versus runoff).

Gap 2.1d: The design of existing forest inventory programs limits understanding of carbon stored in soils, litter, and dead wood, and precludes attribution of tree growth and mortality to disturbances and management. In addition, some disturbance such as wildfire may be incompletely captured with a distributed plot sampling network.

2.2 Knowledge gaps related to a historic emphasis on a limited set of carbon stocks

Even if data are plentiful, **substantial additional uncertainty can be traced to a historic emphasis on two slowly evolving carbon stocks** (or pools); specifically, [1] **soil carbon in the top 30 cm of the soil** in croplands and grasslands, and [2] and **the carbon contained in aboveground plant biomass**. Approaches for estimating the carbon contained in a soil sample, or in a single tree, are well established. In the case of soil carbon, small soil cores are physically extracted from the soil and analyzed for their carbon content in the laboratory. For tree carbon, field measurements of tree diameter and height are collected and used as inputs into empirical (allometric) relationships that describe species-specific relationships between tree size and carbon content. While the accessibility of these measurements is advantageous, linking the mitigation potential of NbCS solely to present-day changes in these pools remains limited in three major ways.

First, **a narrow focus on only two pools misses important carbon sources and sinks and prevents ecosystem-scale assessments of NbCS impacts**[7,112,113] **(Fig. 3).** Soils store a large proportion of carbon in the sub-surface (depths > 30 cm). Yet research on soils has focused on the surface (0-30 cm) as the zone of greatest biological activity that responds most readily to management, and nearly all crediting systems only model or measure down to 30 cm or less[55,114]. Studies that have captured greater depths reveal that certain practices like no-till farming result in a redistribution of SOC such that perceived gains in surface soils may be attenuated by losses at depth[84,115,116]. The lack of data on SOC dynamics at depth hinders our ability to draw robust conclusions and uncertainty remains high[117-119].

In the case of tree carbon, allometric relationships linking tree size and carbon content are typically based on trees that were harvested decades ago. Thus, these allometric models may not incorporate the many ways that climate feedbacks like rising atmospheric CO_2 and increasing drought stress can affect patterns of tree growth and allocation[120-121]. Moreover, while tree biomass is often the fastest-growing pool of carbon in forests, forest soil carbon is a dynamic pool in which most forest carbon resides[123]. A non-negligible quantity of carbon assimilated by trees is ultimately translocated to and stored in the soil each year through root exudates, leaf litter, and inputs from downed woody debris[122]. Moreover, in a world characterized by more frequent tree die-offs, the rates of accumulation in standing and downed dead biomass carbon stocks could increase. Indeed, over the past 10 years, the downed wood biomass of forests in the contiguous U.S. has increased 18% while live biomass has increased only 4%[123]. Finally, a growing body of literature suggests that the link between stem biomass increment and tree carbon uptake (e.g., net primary productivity) is not particularly strong[124-126]. Taken together, **these considerations motivate forest NbCS assessment and accounting protocols that consider ecosystem-scale fluxes and a larger set of carbon pools.**

Second, because ecosystem carbon pools are quite large to begin with, **it can take years for a change in these pools to become detectable,** whereas a change in the land-atmosphere flux can be detected immediately. To understand this limitation, it can be helpful to visualize a swimming pool, representing all the carbon in an ecosystem. Imagine the pool is being filled by a hose (representing the net flux of CO_2 from the atmosphere to the ecosystem), and that there is negligible outflow from the pool (e.g., leaks like the lateral loss of carbon through runoff are small). If the hose inflow rate is doubled (representing the implementation of an NbCS strategy), an observer tracking inflow from hose will be able to quantify the impact of the intervention immediately. However, an observer attempting to infer this flux by tracking changes in the volume of water in the pool will have to wait much longer for the change in inflow to become detectable. Most NbCS accounting and crediting protocols are focusing on the pool, and not the hose. This mismatch has important consequences for the speed with which the climate benefits of individual projects can be quantified. A multi-year delay in understanding if an NbCS treatment is producing the desired outcomes increases uncertainty in implementation programs and limits our ability to rapidly evaluate the effectiveness of emerging NbCS strategies.

Together, these first two issues point to advantages and disadvantages of both flux and stock measurement and detection techniques (Fig. 3). In isolation, ecosystem-atmosphere flux observations are unable to track where carbon is stored in an ecosystem (an important determinant of durability) or the potential for rapid off-site release of recently sequestered CO_2 (e.g., following harvest or lateral export in runoff). Stock change measurements can be ambiguous regarding where carbon comes from and goes to, and may not differentiate between increases in inputs or decreases in outputs. For example, an increase in soil carbon might result from increased litter production because of stimulated plant growth, which would cause a reduction in atmospheric CO_2, or from enhanced litter production due to disturbance, which would

not lower CO_2 concentrations. Both stock and flux approaches are incomplete without the other. **We need confident tracking of carbon fluxes and stock changes with holistic tracing of carbon flows throughout the system.**

	Stocks	v	Fluxes
Net land-atmosphere uptake/emission	🟡		🟢
Harvest & lateral fluxes (runoff)	🟡		🔴
Allocation to different pools	🟢		🔴
Biophysical impacts	🔴		🟢
Non-CO_2 greenhouse gases	🔴		🟡
Latency of impact detection	🔴		🟢
Cost & technical skills	🟢		🟡
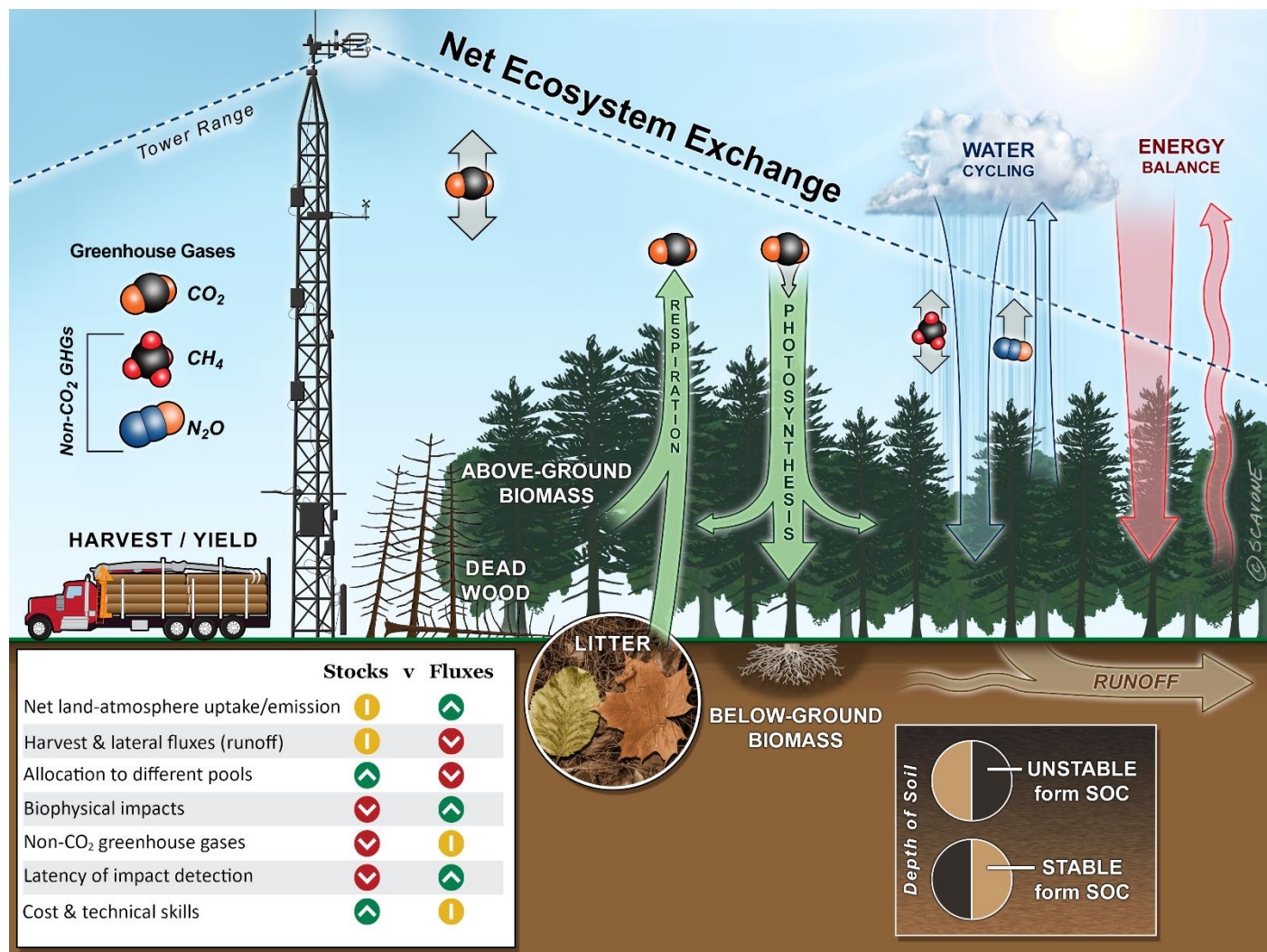
Figure 3. An illustration of key ecosystem fluxes (arrows) and stocks (or pools, white text). Flux towers provide ecosystem-scale measurements of the net ecosystem exchange of CO_2 between the land and the atmosphere, and some towers can also measure the land-atmosphere flux of methane and nitrous oxide. Because towers record information continuously, they can quickly detect the impact of changes in land cover and management, especially when deployed in an experimental setting. Their ability to continuously measure ecosystem-scale water and energy fluxes also makes them particularly useful for understanding biosphysical impacts. However, flux towers are not able to monitor carbon lost to harvest or runoff, and provide little information about the allocation of sequestered carbon to different pools. On the other hand, changes in ecosystem stocks will reflect the combined influence of inputs (e.g., sequestration/emission) and outputs (e.g., harvest/runoff) on pool sizes. Depending on how many pools are monitored, theses observations also provide more granular information about how sequestered carbon is allocated (e.g., to above versus belowground pools, including more stable versus more unstable forms of SOC). For these reasons, flux and stock measurements are best viewed as complimentary. The table in the lower left illustrates the relative advantages and disadvantages of each approach. Green symbols indicate an advantage, red symbols indicate a disadvantage, and yellow symbols indicate that the relative strengths likely depend on context and measurement design. Image copyright William Scavone. All rights reserved.

Third, focusing on carbon stocks alone prevents a more holistic understanding of the overall GHG emission benefits (or unintended consequences) of a given NbCS strategy. Specifically, **carbon stock changes are insufficient to understand NbCS impacts on emissions of non-CO₂ GHGs** like methane and nitrous oxide, which are particularly important to consider in wetlands and many agricultural systems. We urgently need strategies to resolve NbCS-driven changes to these GHGs with a precision that overcomes uncertainty due to natural variability.

Box 2.2: Knowledge gaps related to a historic emphasis on a limited set of carbon stocks

Gap 2.2a: NbCS assessments and protocols lack ecosystem-scale perspectives that integrate over all relevant carbon sources and sinks.

Gap 2.2b: Limited ability to quickly quantify the actual benefit of NbCS on the ground.

Gap 2.2c: Limited undrestanding of NbCS impacts on methane and nitrous oxide emissions.

2.3 Knowledge gaps preventing policy-relevant mapping of NbCS mitigation potentials

The potential climate benefits of a given NbCS strategy will vary from one location to the next, reflecting differences in climate, underlying soils, topography, and historic management regime. If the goal is to incentivize NbCS to maximize their climate benefits, **the most robust NbCS implementation programs would be designed with an understanding of where and when a given strategy is most likely to succeed** and would avoid allocating resources to interventions that do not offer tangible climate benefits. Unfortunately, **spatially explicit maps of climate change mitigation benefits for most NbCS strategies are scarce.** This is especially true for agricultural and wetland NbCS. At the time of this writing, to our knowledge, there are no published maps that rigorously describe the carbon uptake benefits, or biophysical impacts, of cover crops across the Corn Belt. **Overall, a major factor limiting our ability to map the climate benefits of agricultural and wetland NbCS is a lack of representative data that spans many axes of variability** (e.g., soils, climate, species, historic management, land ownership history).

There are a couple of exceptions. No-till agriculture has been widely studied through paired plot experiments, motivating several meta-analyses that incorporate field data into models that relate changes in soil carbon to mappable environmental drivers, yielding spatially explicit estimates of carbon sequestration potential[127,128]. However, recent work reveals that the change in soil carbon under no-till management varies as a function of both time and depth into the soil; and efforts to extrapolate estimates of the change in soil carbon to regional- and continental-scale may lead to misleading conclusions[116]. Likewise, mitigation potential maps of forest-based strategies – and especially reforestation – are relatively abundant. Data on aboveground biomass provided by inventory networks like FIA are fairly complementary with remotely-sensed proxies for forest biomass (e.g. from GEDI[129]) as well as a suite of existing models and carbon monitoring frameworks[130,131] that predict carbon uptake based largely on changes in biomass. Nonetheless, **mitigation potential maps will only be as robust as the underlying data;** if these maps are informed primarily by changes in carbon stored in shallow soils and/or aboveground woody biomass, they will suffer from the same limitations described in the preceding section.

The spatial resolution of mitigation potential maps will ultimately be determined by the representativeness of the ground data used to train the scaling algorithms, and the resolution of the remote sensing products and models used for extrapolation. Maps at a resolution that matches the scale of individual farms and forest stands are likely infeasible in the near term. However, maps made at relatively fine scales (e.g. county-scale) may be possible for some NbCS strategies.

> **Box 2.3: Knowledge gaps preventing policy-relevant mapping of NbCS mitigation potentials**
>
> Gap 2.3a: Especially in agricultural and wetland systems, we lack spatially-resolved maps of NbCS mitigation potentials, preventing an understanding of when and where these strategies are most likely to succeed. This gap is linked to a scarcity of representative ecological and socio-economic data.
>
> Gap 2.3b: In forests, existing potential maps are primarily informed by data on tree biomass change, which miss other important carbon pools.

2.4 Knowledge gaps preventing a holistic assessment of NbCS biophysical impacts

Any intervention designed to affect carbon cycling will have a concomitant impact on water and energy cycling (hereafter "biophysical impacts"), as these three cycles are closely coupled[132]. For example, due to the link between photosynthetic capacity and stomatal conductance[133], greater ecosystem photosynthesis is typically associated with greater evapotranspiration[46]. All else being equal, an increase in evapotranspiration is likely to decrease soil moisture and runoff. Whether this is a favorable outcome greatly depends on the local climate regime, time of year, and management goals. For example, greater springtime evapotranspiration (e.g., linked to cover crop use) may be welcomed by producers throughout much of the Corn Belt, where saturated conditions can delay or even prevent planting of cash crop seeds[134]. Conversely, when and where soil moisture deficits are common and limit agro-ecosystem productivity, alterations to the hydrologic cycle that further deplete soil moisture would be undesirable. With some exceptions[46,135,136], systematic frameworks for understanding how NbCS impact carbon and water cycles are rare, and **more holistic assessments of coupled carbon-water impacts of NbCS are urgently needed.** This is also critical for ensuring water management strategies are consistent and complementary with climate mitigation efforts, especially as water availability becomes less predictable.

Land cover and management shifts also affect energy budgets in ways that can impact temperature directly[137]. For example, replacing relatively light colored (high albedo) grasslands with darker (low albedo) forests will increase solar radiation absorbed at the surface, which can have a local warming effect. However, at the same time, forests tend to use more water (higher evapotranspiration) and generate more effective transport of heat energy away from the land surface (increased sensible heat flux). Both mechanisms tend to cause surface cooling at local scales[138,139].

Arguably, for some categories of NbCS, our understanding of local temperature impacts is more advanced than our understanding of carbon cycle impacts. While no remote sensing platform is yet capable of sensing the net carbon flux directly, satellite estimates of land surface temperature and surface albedo have been widely available for decades. Moreover, flux towers measure all the relevant terms of the ecosystem energy budget. When deployed in a paired-site setting[139,140], flux towers can tell us not only how local surface temperature is affected by a land cover or management shift, but also which underlying mechanisms are responsible for the shift[138,139,141,142] Collectively, these data products have been widely used to demonstrate that NbCS strategies in some regions have an overall local surface cooling effect (e.g., tropical and temperate zone reforestation[135,143,144]; wetland restoration[145], and conversion to frequently flooded agriculture lands[146]). In other cases (e.g., semi-arid and boreal forests), the radiative impacts of NbCS may lead to additional warming[141,147]. Nonetheless, **the consequences for local surface temperature have not been rigorously quantified for many categories of NbCS.** For all NbCS strategies, more work is necessary to **understand the relationship between local surface and air temperature impacts**[148,149], especially during climate extremes like heat waves[150,151].

Importantly, local temperature responses to NbCS do not necessarily scale up to regional or global temperature changes. In isolation, a decrease in albedo will tend to cause both local and global warming. To the extent that NbCS increase evapotranspiration that results in increased cloudiness, they may cause reductions in planetary albedo which has a

cooling effect[137]. But on the other hand, heat diverted from the surface through enhancements to evapotranspiration and sensible heat flux is re-released in the atmosphere and does not escape the planetary climate system. **Consequently, changes in local surface temperature are not necessarily correlated with a global climate system response, making changes in local surface temperature an incomplete indicator of the biophysical impacts of NbCS[131,152,153].** Although these mechanisms are broadly understood by meteorologists and climate scientists, they are not always considered by practitioners or even some scientists working with NbCS.

Finally, evidence from modeling studies suggests that modifications to energy and water cycling in one location can have downstream effects on water and energy cycling in other locations through non-local effects and so-called "eco-climatic teleconnections"[154,155]. Right now, our understanding of these non-local effects is limited to what we can learn from **climate models, which often struggle to characterize resulting temperature changes with sufficient precision** to match the scale of NbCS interventions.

Box 2.4: Knowledge gaps related to biophysical impacts

Gap 2.4a: We lack a comprehensive framework for understanding how NbCS impact local water cycling.

Gap 2.4b For most categories of NbCS, we lack a rigorous quantification of biophysical impacts for surface and air temperature at local to planetary scales.

Gap 2.4c Climate and land surface models struggle to reproduce the direct temperature impacts of NbCS with enough precision to quantify local and non-local biophysical impacts.

2.5 Knowledge gaps limiting predictions of durability and disturbance risk

2.5.1: The importance of durability for robust NbCS: Durability refers to the period of time over which carbon removals or avoided emissions that result from an NbCS intervention persist without failure. The term is used in practice to characterize the duration for which carbon mitigation from a particular policy, market, or program is assured to remain out of the atmosphere. Durability depends on relevant physical and ecological risk factors that can lead to "reversals" through which carbon or other GHGs return to the atmosphere. For example, carbon stored in forests is vulnerable to mortality events driven by wildfire, drought, disease, and insects[156]. In many instances, durability also depends significantly on program governance features[50], such as whether a parcel of land has committed to maintain climate-smart practices by contract or by easement, as well as whether a program includes insurance mechanisms to address reversal risks[157]. As a result, properly characterizing the durability of NbCS requires insights from natural and social sciences, as well as assessments of environmental economics and policy.

Long-lasting **durability is essential whenever NbCS are used to offset or otherwise justify CO₂ emissions.** CO₂ emissions from fossil fuel burning alter atmospheric concentrations on an effectively permanent basis, with the most pronounced effects on the order of two to 20 centuries and a substantial residual persisting on geologic timescales[158,159]. Although this temporal discrepancy indicates that CO₂ stored in biological carbon sinks is not equivalent to fossil CO₂ emissions on a per-mass-unit basis[160], many carbon market applications assume that "a ton is a ton" regardless of whether the ton is stored temporarily in short-duration storage or permanently added or removed from the atmosphere. Today, **most NbCS accounting and monitoring systems generally do not feature significant recognition of the temporary nature of ecosystem carbon storage,** and differences in the temporal dynamics of credited carbon are often not reflected in valuation[51].

The extent to which durability is broadly relevant in non-offsetting contexts is a more nuanced question. Ambitious modeling of deep decarbonization combined with temporary carbon removals indicates that temporary removals can

play a relevant role in climate mitigation[11]. These contributions depend on the use of temporary carbon storage in nature-based systems in addition to, rather than instead of, reductions in CO_2 emissions. Even when deployed in this manner, the benefits of temporary carbon removals depend critically on the timing and durability of storage achieved. Progress is underway to better define the value of temporary carbon storage when it is significantly less durable than CO_2 emissions[161,162] so that we better understand the usefulness of temporary storage in reducing and slowing warming in the decades ahead.

2.5.2: Our current understanding of NbCS durability: In forested ecosystems, the scientific community has high confidence in several key findings around forest-based NbCS and their potential durability. First, we understand fairly well the spatial patterns of *relative risk* for a number of key climate-sensitive disturbances, such as fire, drought, and insects[30,63,163-166]; Second, we have very high confidence that climate change is already increasing these risks in many regions of the world[163,167,168]. Third, the extent of climate risks to forests are increasing dramatically, and probably non-linearly, with the amount of climate change[156,168]. The existing knowledge gaps largely concern when and where management can meaningfully reduce long-term permanence risks, and to what extent disturbance risk is coupled with carbon storage capacity in the near term[30,169-172]. Closing these gaps requires better understanding of trajectories of forest recovery, regeneration, and regrowth dynamics after climate-driven disturbance, and better tools for translating relative disturbance risk into absolute risk to carbon storage.

In soils, where land use, land management and climate can all act to reduce soil carbon levels, direct measurements of the form of carbon accumulating in soil is critical[173]. If newly sequestered carbon ends up in mineral-protected, aggregate-protected, and other stable forms of SOC, then there is a greater chance this new SOC will persist[174,175]. Similarly, the oxidizing state of the storage environment (oxic or anoxic) can play an enormous role in SOC stability. This suggests that measurement of total SOC stocks alone is not sufficient. Rather, **we also need to measure the forms (or fractions) of SOC that are accumulating and the environment in which they are accumulating[176]**.

For certain agricultural and hybrid approaches, perceived advantages in durability must be rigorously proved. In the case of biochar, for example, the carbon residence time in soils depends strongly on pyrolysis temperature[177,178] with only the highest temperature biochar having a half-life of more than 1000 years. Biochar may also reduce soil nitrous oxide production, but the effectiveness of this reduction also depends on biochar pyrolysis temperature. For proposed anoxic storage of wood ("wood vaults") with ensuing regrowth, durability may stretch to centuries, but additional research is necessary[45]. Release of methane and CO_2 from the "vaults" also requires assessment.

For all NbCS, the **socio-ecological factors that determine landowner decision making about NbCS practice adoption and abandonment remain highly uncertain[58,179]**. These choices, ostensibly made by individual land managers, are strongly shaped by environmental, social, and economic interactions and feedbacks operating over multiple scales. Policy-driven incentives, and macro-scale economic dynamics, greatly determine which practices are adopted. Social networks and norms play an important but underappreciated role in influencing management decisions of individual land managers[180]. Further, for all NbCS, **non-linearities in permanence risks and how they will interact with other climate-change mitigation efforts are important** to consider. For example, NbCS are likely much more reliable in a low emissions future with more modest climate change than in a high emissions future.

2.5.3: Predicting durability using models: Use of mechanistic ecosystem models offer a theoretical approach for forecasting durability into an uncertain future[181-183]. Indeed, this is the only way to project how climate feedbacks will ultimately affect the rate of carbon transfer into and out of ecosystems. The carbon cycle science community has a long history of ingesting field and satellite data into mechanistic model frameworks for benchmarking and to improve model parameterization[65,66,184-188]. Uncertainty in model-based predictions can be large, due to various reasons, including the omission or oversimplification of critical processes, and a lack of observational constraints for model parameters. For example, some models designed specifically to be embedded within Earth System model frameworks (e.g. the Community Land Model[189]) have historically lacked representation of agricultural management, soil priming, forest demographics, and fire, though this is changing[190-194]. These models are also frequently applied at spatial scales too coarse to inform individual NbCS projects, or at finer scales but with a computational cost that limits their usefulness for regional policy setting.

Exceptions exist[36], including DNDC[195] and DAYCENT[196]. Daycent is a process-based model that is now widely applied in earth system modeling frameworks[197] and informs the USDA COMET-Farm decision support tool[198], effectively spanning the divide between global-scale predictions necessary to inform future climate states and applications to support present-day management, including carbon crediting[55]. However, like all models, DAYCENT requires representative data to ensure efficient and accurate quantification at regional and continental scales[199], which is lacking in working lands (see Sections 2.1 - 2.3).

There is an ongoing need to continually update model structures so that they represent NbCS-relevant processes at NbCS-relevant scales. Moreover, integrating state-of-the-art ecological theory and data sources into model structures and workflows remains challenging, stemming from a divide in the expertise necessary to develop new theories and test them in the field, and the expertise required to implement theoretical understanding in ecosystem models. One way to bridge this gap is to increase the accessibility of models, by making them easier to compile and parameterize, so they can be used in more cross-disciplinary settings to address a broader range of research questions. Towards that end, existing initiatives like the Predictive Ecosystem Analyzer workflow (PEcAn[200]) and evolving frameworks for integrating new mechanisms into modeling frameworks[201,202] can serve as useful examples.

Box 2.5: Knowledge gaps limiting predictions of durability and disturbance risk

Gap 2.5a: The absolute durability risks from physical and socio-economic processes remain poorly understood and are not rigorously considered in most project-scale NbCS accounting schemes.

Gap 2.5b: More representative data is needed on the form in which carbon is stored in soils, and on the trajectories of ecosystem recovery following climate-driven disturbance.

Gap 2.5c: The existing set of ecosystem models requires more robust representation of NbCS-relevant mechanisms at NbCS-relevant scales, and continued efforts to make model frameworks more accessible to diverse end-users.

2.6 Additional knowledge gaps that hinder credible accounting of NbCS projects

2.6.1 - Challenges related to carbon offsets: Most of the programs incentivizing and crediting NbCS activities center on carbon offsets and fall into one of two categories: compliance programs run by governmental entities (e.g., the California Compliance Offset Program) or voluntary programs run by non-governmental organizations (e.g., Verified Carbon Standard)[203]. Offset programs develop and approve standards for the quality of carbon offset credits, review offset projects against these standards, and operate registry systems that oversee transactions of offset credits. Resulting credits are traded and exchanged in market systems, allowing a wide range of buyers to invest in climate-positive management practices, often for the purpose of offsetting emissions from elsewhere in their operations or supply chain. However, **without consistently high standards, carbon offset credits risk accelerating rather than mitigating climate change while potentially exacerbating localized cumulative pollution for vulnerable communities near emitters.**

Credibility of these carbon credit and offset programs requires reliable and accurate data and transparent and repeatable methods, both of which need to be evaluated by trusted, independent and financially uninterested parties. Right now, **approaches for monitoring and verifying carbon benefits vary substantially from one market entity to the next**, and **protocols lack rigorous cross-comparison and standardization against common datasets**. This lack of standardization and verification limits the system-wide equivalency of carbon credits and erodes confidence in the quality of carbon offsets. **Many of the approaches and protocols being used to scope and evaluate carbon offsets lack transparency and cannot be externally examined because data and methods are not open source.** Further, projects are not always required to provide all the data and information needed to recreate and independently verify methods and assumptions.

For example, a recent effort to document and synthesize 12 publicly available protocols for generating agricultural soil carbon credits[55] revealed inconsistencies in how different crediting programs measure and estimate SOC sequestration and net GHGs, and how they account for additionality, leakage, permanence, and uncertainty. Some protocols only provide credit for soil carbon sequestration, failing to account for other potent GHGs like nitrous oxide and methane. Some protocols suggest that crediting only SOC sequestration is more conservative, because participants are not receiving additional credit for emission reductions of nitrous oxide, but this approach runs the risk of neglecting emissions such as those associated with fertilizer use. Moreover, these protocols lack incorporation of best-practice sampling approaches for soils. We know fixed depth accounting of carbon stocks (measuring carbon to a fixed depth versus an equivalent mass) may bias stock estimates due to changes in soil bulk density[204-206]. However, very few protocols require accounting on an equivalent soil mass basis which can lead to systematic over- or under-accounting.

For forests, there are a range of approved voluntary and regulatory protocols providing technical guidance on carbon credit generation, including through avoided conversion and improved forest management projects[207,208]. While forest carbon offset projects are allowed within existing U.S. regulatory markets, including the California[209] and Regional Greenhouse Gas Initiative (RGGI)[210] cap-and-trade programs, their future role remains uncertain. For example, although forest projects have been allowed in RGGI since 2009, no forest carbon credits have been generated to-date. This is likely due to the relatively low trading price of RGGI allowances and the labor and cost-intensive nature of the existing protocols. Elsewhere, forest offset programs are being heavily scrutinized. For example, California's compliance market has been criticized for systematic over-crediting; specifically, Badgley et al. (2021)[52] found that by averaging together dissimilar tree species across arbitrarily defined geographic regions, the California program enabled payment of upfront credits to specific projects based on non-real outcomes.

As forest carbon credit protocols are evaluated and improved, the most successful efforts are likely to be those which can maintain acceptable levels of uncertainty while harnessing new cost-effective technologies for quantifying and verifying reductions across large spatial domains, including using remote sensing technologies. These economies of scale are critical for addressing the many socio-economic challenges regarding project implementation, including small project aggregation to reduce overall transaction costs[211] which are currently a major barrier to participation from owners of small land areas. A recent review of existing forest protocols discusses these and other socio-economic barriers alongside several well-established methodological challenges related to additionality, permanence, and leakage[212].

2.6.2 - Alternatives to crediting: In addition to voluntary or state-run carbon markets, there are other options policy makers may wish to consider for incentivizing implementation of NbCS. These mechanisms include (1) federal or state incentives, (2) certifications and standards such as performance or efficiency standards, and (3) fostering increased consumer demand and corporate responsibility for climate mitigation, including NbCS.

· **Federal and state Incentives** are typified by Farm Bill Conservation Programs that provide direct assistance to farmers to improve habitat, soil, and water quality. Two of the largest incentive programs are the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP) of the Natural Resources Conservation Service. EQIP funds are generally used to initiate new on-farm conservation practices while CSP funds tend to support continued use of existing practices. At the state level, Maryland and Delaware have long provided incentives to plant cover crops to reduce nutrient runoff. In Maryland, cover crop incentives in 2022 started at $55/acre with additional payments for an early start, late finish, or specific mixtures. As a result, these states have by far the highest cover crop adoption rate[213]. Similarly, California runs a Healthy Soils Program to encourage on-farm soil carbon sequestration[214].

· **Certifications and standards** represent another alternative to crediting approaches. For example, the Forest Stewardship Council (FSC) certification has been a leading forum for denoting sustainably sourced wood products for the past three decades. FSC certification focuses on adoption of practices that protect and enhance forest health and biodiversity, which often also increase carbon sequestration[215]. Another relevant example is the USDA's recent $2.8 billion dollar investment in more than 70 "Climate Smart Commodity"[216] pilot projects (selected from more than 450 proposals), designed to "create market opportunities for American commodities produced using climate-smart production practices." Emphasizing the need for improved quantification, all projects were required to submit plans for measuring GHG benefits over time, including by using models, remote sensing, in-field testing, and other methods.

· **Corporate responsibility for climate impacts and climate mitigation** is a more recent and fast-growing mode of incentivizing NbCS implementation in the private sector. For example, more than 3500 companies globally have committed to setting Science-Based Targets to mitigate their GHG emissions[217]. Taken together, these companies represent more than 35% of global market capitalization. Companies that set Science-Based Targets agree to reducing emissions from their own operations and from within their supply chain in line with what is needed to be aligned with a 1.5 °C future. Prior to Science-Based Targets, many NbCS were financed by the voluntary carbon market, and sold as offsets, to compensate for emissions elsewhere. Science-Based Targets have brought NbCS into corporate supply chain target setting. Consequently, they cannot use NbCS as offsets to compensate for their energy or industrial emissions.

These new approaches have the potential to overcome the more problematic aspects of carbon offset crediting. However, critical information needs remain, including rigorous evaluation and cross-comparison of protocols for monitoring and verifying the realized impact of these practices, coupled with robust durability projections.

2.6.3 Baselines and additionality: Regardless of the tools by which they are incentivized, successful NbCS rely on a **demonstration of additionality over a "business-as-usual" baseline approach**. The requirement of additionality means that a program or policy must induce marginal new benefits that go beyond what would have happened in the absence of the market or other policy tools to incentivize NbCS. Additionality is defined by comparing a *project scenario* in which planned activities occur against a counterfactual *baseline scenario* that describes what one expects would have happened under business-as-usual conditions. An obvious solution to this challenge is to match the NbCS project "treatment" area with a similar, nearby "control" area that will be sustained under traditional management regimes. Some market entities are beginning to adopt this approach[61,218], but this practice is not yet common. Instead, the entire project area typically experiences the NbCS intervention, such that the counterfactual scenario cannot be directly observed because it does not exist. **Consequently, right now, baselines must be modeled or estimated indirectly, which represents a major source of uncertainty in NbCS quantification schemes.**

Models used to estimate baselines tend to be computationally inexpensive algorithms that were developed decades ago, for purposes that did not include precise quantification of changes in GHG emissions in specific landscapes in response to specific management interventions. **While some of these models used to predict baselines have been subjected to systematic benchmarking[219], many others have not.** Moreover, forest growth models like the USDA Forest Vegetation Simulator (FVS[220]) do not explicitly account for climate-change feedbacks to forest growth or mortality, yet are being used in many accounting schemes to make 100-year projections of forest carbon stock change. And because **most baseline estimation approaches are strongly focused on the changes in two limited stocks of carbon** (e.g., shallow soil carbon and carbon in aboveground plant biomass)**, baselines estimation will suffer from the same limitations as the underlying data** (see Section 2.2).

Projecting a reasonable baseline scenario is especially challenging because many programs allow baselines to be constructed by project proponents — that is, by those who are seeking financial compensation[221]. Project proponents tend to know more than policymakers about the realm of possibility and the plausibility of various claims, with this information asymmetry limiting the ability of policymakers to exercise independent judgment (Bushnell, 2012). Experience with the largest carbon markets suggests that letting individual projects propose baseline scenarios has led to highly non-additional outcomes[222-225].

Among our workshop participants, there was **strong agreement that defining the business-as-usual baseline is one of the biggest challenges and most critical components of accurately quantifying NbCS mitigation benefits[112]**. One proposed solution is the development of **standardized baselines, through which regulators identify a consistent approach to baseline scenario construction that all project proponents must apply[226]**. A key advantage of this approach is that it can be explicitly designed to estimate over- and under-crediting and seek to balance expected outcomes at a portfolio level[227]. For example, if policymakers are concerned that a particular approach to establishing a baseline scenario could allow some non-additional projects to opt in and earn credits, they can explicitly adopt discount factors or other parameter choices that are calibrated to mitigate these anticipated effects at the portfolio level. While these design choices hold the potential to mitigate non-additionality risks, they require significant judgment calls that effectively embed many of the same risks in policymakers' standardized protocol design rules[226,228]. Moreover, a key concern with standardized baselines is the problem of adverse selection. Once a standardized

baseline rule is in place, it creates an incentive for projects that receive excessively generous treatment to participate while reducing the incentive for projects that receive insufficiently generous treatment[229-231]. This effect has been demonstrated at large scale in California's forest carbon offsets program, which uses standardized baselines to award credits based on broad regional averages that do not reflect project-level ecology[52,232]. Monitoring program implementation for possible adverse selection effects requires high-resolution data, rigorously benchmarked scaling tools, and transparent reporting criteria that permit program managers to rapidly identify and correct for any unintended effects.

There was also **strong consensus among workshop participants that dynamic baselines represent a preferred path forward.** A dynamic baseline is one that varies in time, reflecting ecosystem responses to variable environmental conditions and considering long-term shifts in ecosystem composition and structure. One approach that is already being adopted or proposed by at least two market systems (e.g. Verra's ABACUS label[61] and the American Forest Foundation Family Forest Carbon Program[218]) is the pairwise matching of project and control areas for program implementation. For most ecosystem ecologists, this is a familiar concept, as the field has a long history of evaluating how a strategic land cover or management shift applied to a "treatment" plot (in this case, the area of land receiving NbCS-relevant management) affects ecosystem processes when referenced to a nearby "control" plot. It also borrows techniques used to establish ex-post control groups and compare project outcomes in relation to controls[64] but deploys them instead on an ex-ante basis. Another approach is to harness information from robust, representative monitoring networks together with remote-sensing data to create dynamic baseline maps at scales that are reasonably well matched to the scale of NbCS projects. **Efforts to validate both field-level and remote-sensing enabled approaches to quantifying dynamic baselines is a major research need.**

Leakage is another important consideration that is not rigorously considered in most crediting protocols (but see Verra ABACUS[61]). Leakage is a particularly pressing concern for any NbCS that may reduce yield. For example, in the absence of altered market demands for wood products, avoided deforestation in one place may simply lead to forest clearing in another place[233]. In cropland systems, adverse impacts on yield are also possible, and new fundamental research is needed in areas like cultivar development and soil microbiome improvement to provide resilience against potentially negative consequences of NbCS on harvestable yield. Leakage is not rigorously quantified in most crediting protocols, and measuring it is a difficult task. Economic models that incorporate land cover change, or maps of forest structure at a resolution sufficiently fine to detect removals and conversions, may make it easier to quantify leakage in the future.

Finally, as discussed already in Section 2.5, **durability is critical for effective NbCS interventions but is rarely treated adequately in existing accounting and crediting frameworks**. Risks of failure tend to be poorly quantified or even ignored. Also needed are **policy and governance mechanisms for sunsetting problematic past practices** that have failed to live up to the necessary standards. These "off-ramps" will be needed to improve quality, to facilitate adoption of better standards and to stand up new registered protocols and practices.

Box 2.6: Additional knowledge gaps that hinder credible accounting of NbCS projects

Gap 2.6a: The protocols used in practice to monitor and verify NbCS project benefits are extremely diverse and lack systematic cross-comparison and standardization across common data sets.

Gap 2.6b: Approaches for creating standardized and/or dynamic baselines to determine additionality have not yet been fully developed or systematically benchmarked.

Gap 2.6c: Methods for calculating and valuing durability, disturbance risk, and leakage in accounting protocols are either absent or lack standardization or a rigorous evidence basis.

3. The Best Available Tools and Technologies

The dominant role of terrestrial ecosystems in determining atmospheric CO_2 concentrations has been known for decades. Consequently, huge investments of material resources have fostered innovative measurement approaches, analytical tools, and models for quantifying ecosystem carbon cycles. These tools are described below and in Figure 2.

3.1 Repeat field measurements of carbon stocks: Routine monitoring of ecosystem carbon pools remains a critical tool for monitoring changes. They can provide powerful insights when deployed in experimental designs that monitor control areas relative to treated areas experiencing NbCS interventions. Moreover, carbon stock measurements do not require extensive data post-processing or highly specialized expertise, which increases their accessibility. Long-term observational networks that include standardized stock measurements are important for baseline monitoring, and their stratified distribution enables not only detection of changes but also insights about their attribution. There is a rigorous and growing literature on optimal sampling design that can inform field monitoring campaigns[234-236].
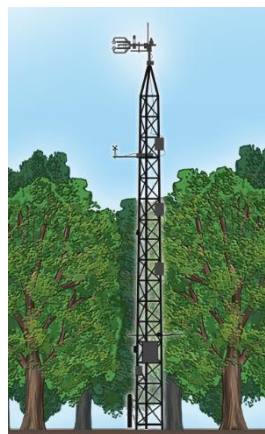
3.2 Flux towers and flux tower networks: Flux towers permit continuous, ecosystem-scale observation of the movement (or flux) of GHGs, water, and energy between ecosystems and the atmosphere, enabling holistic assessments of how NbCS affect not only carbon uptake, but also exchanges of other GHGs (e.g., methane and nitrous oxide) and concurrent biophysical impacts on local temperature and water cycling[113]. Critically, they integrate across both above- and below-ground sources and sinks and provide continuous measurement that permits rapid quantification of the impacts of an intervention or disturbance[7]. Flux towers also record a wealth of supplemental data on meteorological and soil variables that can be used for building mechanistic links between fluxes and short- and long-term variability in environmental conditions. Data from flux towers operated by individual research teams have been aggregated into networks that provide support such as data standardization, toolkits for analysis, consistent calibration protocols, and other services[7,65]. These standardized network data products provide an invaluable source of benchmarking data for modeled and remote sensing products[237,238]. These networks are consistently tested for their representativeness. They tend to include many temperate ecosystems, but sites from drier regions, the arctic, and the tropics are not as well represented[239,240]. Flux tower networks have not yet been assessed for their representativeness of ecosystems managed with NbCS-relevant regimes.
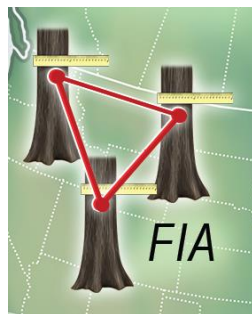
3.3 The USDA Forest Service Forest Inventory and Analysis (FIA) program: The FIA program provides information about the distribution of, and trends in, aboveground tree carbon stocks at the continental scale. The program was designed for large-scale inference of forest trends, and the FIA is the primary source of information for U.S. reporting of forest carbon to the United Nations Framework Convention on Climate Change[241] (i.e., COP21 commitments). The regularly scheduled (e.g. 5-10 year) sampling of long-term monitoring plots for data on tree species composition, size, and health enables mapping of the change in aboveground carbon biomass at policy-relevant scales[70,71]. Information on mortality rates available from FIA has proven extremely useful for estimating disturbance risk that can inform projections of the durability of NbCS benefits[30]. Likewise, long-term species composition data from FIA have been successfully integrated with information from ecophysiological trait databases to better understand how species composition shifts driven by management and climate change will affect carbon sequestration potential in the long term[242]. However, as discussed in section 2.1, FIA was not designed with the explicit goal of informing project-scale forest based NbCS, and some features of the program limit its usefulness for NbCS decision support. Moreover, the national Forest Health Monitoring program, a partnership between the USDA Forest Service, state-level forestry agencies, and other federal, state, and academic groups, provides detailed and extensive information on trends forest mortality and disease status through aerial and ground surveys and plots, which have been hitherto overlooked and underutilized for NbCS assessments.

3.4 Spectroscopic technologies and other approaches for proximal soil sensing: Diffuse reflectance spectroscopy in the mid- and near-infrared range is an emerging approach for quantifying soil carbon and several other soil properties relevant to carbon cycling[243-245]. Mid-infrared spectroscopy can also be useful for estimating the fractionation of SOC (e.g. particulate versus mineral-associated)[244]. This technique permits rapid and cost-effective quantification of SOC[246] in both the laboratory and, with emerging sensor technology, in the field[247]. Important questions remain about the role of environmental conditions and sampling protocols in determining inter comparability of spectroscopic soil carbon data from one site to the next[248]. Despite these limitations, the technique is a promising alternative to chemical analyses in the laboratory[249].

3.5 Tree rings and cores: Tree-ring data are direct, on-the-ground measurements of historic annual tree stem growth, which can be extended into estimates of aboveground biomass accumulation[250-254]. They complement forest inventories like the FIA Program, which lacks the annual resolution needed to detect the sensitivity of forest productivity to interannual climate variability, and in particular the effects of emerging extreme climate events such as heat waves and drought. While existing tree-ring data are affected by sampling biases[255,256] and generally lack information about tree size and other factors key to forest carbon scaling, they are unquestionably the best source of information on the climate sensitivity of tree growth. If sampled in the context of FIA or other forest plot network (i.e., ForestGEO[257] and state- and tribal-level forest monitoring), tree-ring data can foster an unbiased, representative, spatio-temporal data network[253] that addresses many of the gaps concerning the temporal dynamics of forest NbCS.

3.6 Next-generation satellite remote sensing products: Over the past decade, operational, near-real time observations of carbon cycle pools and fluxes have been enabled by multiple active NASA science missions have relevance to NbCS, including the 'Orbital Carbon Observatories' OCO-2 and OCO-3[258,259], and the Greenhouse Gases Observing Satellite GOSAT[260], as well as airborne campaigns providing 'snapshots' of both natural and anthropogenic fluxes at the landscape scale (e.g., CarbonMapper[261], CARAFE[262], and NEON's AOP[263]). NASA's Carbon Monitoring System (CMS) Program, initiated in 2010 by Congressional direction, is a particularly relevant initiative. CMS leverages a full range of NASA satellite observations, modeling and analysis capabilities, and commercial off-the-shelf technologies to develop high-resolution carbon data products for use by a wide range of stakeholders. CMS applications include forest biomass carbon mapping[264,265] and mapping the global distribution and structure of mangrove forests[266]. These examples highlight the potential of satellite remote sensing for monitoring changes in aboveground biomass carbon stocks, enabled by recent missions such as NASA's Global Ecosystem Dynamics Initiative (GEDI)[129], which uses space-based LiDAR to produce global maps of estimated standing biomass. Planned missions, including the European Space Agency's (ESA) Biomass Earth Explorer Satellite and private sector biomass monitoring initiatives from Planet Labs, CTrees, Salo Sciences, and Chloris Geospatial also hold much promise. Even with these developments, further advances would likely be needed to enable repeat measurements with sufficient accuracy and precision to capture small changes that can add up over large areas, as well as large losses over small areas.

Looking forward, opportunity exists to move more fully leverage remote-sensing products that provide information not only on ecosystem structure, but also ecosystem function. For example, missions like NASA's OCO-2 and OCO-3 and ESA's upcoming FLEX (Fluorescence Explorer)[267] provide information about solar-induced fluorescence (SIF), which is a proxy for photosynthesis. Major new satellite hyperspectral missions from both NASA and European countries, such as NASA SBG[268], the Italian Space Agency's PRISMA[269], ESA's CHIME[270], EnMAP[271], and the German Space Agency's DESIS[272] all carry great potential to leverage hyperspectral information to understand ecosystem function and structure. When combined with rigorous ground truthing data, next-generation satellite observations could inform priority-setting by identifying areas with high NbCS mitigation potentials. Novel satellite data could also play an essential role in

compliance regulation, for example through the automated detection of the implementation of strategies such as cover cropping[273,274]. Moreover, missions like ECOSTRESS (which provides information about the dynamics of evapotranspiration and surface temperature at a 70 x 70 m spatial resolution[275]) are especially promising for field-scale mapping of the biophysical impacts of NbCS. Although not traditionally used by carbon registries, space-based observations are increasingly recognized as pivotal to reducing project costs and increasing scalability. Field observations from networks will remain critical sources of ground-truthing data for the next-generation of NbCS-relevant remote sensing missions and data products.

3.7 Predictive models: Spatially explicit and forward-looking NbCS assessments are not possible without the use of predictive models. Indeed, models are already used to interpolate ground observations into regional-scale potential maps[70,108], to estimate NbCS project baselines (including DAYCENT[198] and FVS[220]), and to calculate the relative disturbance risk in forests[30]. But especially in the forest sector, many models used for these objectives tend to be statistical or empirical, relying on observed relationships between driver and response variables that are challenging to extrapolate into a future characterized by climate conditions profoundly different than those experienced historically. These empirical approaches can include traditional regression-based or decision tree approaches[276], as well as emerging machine learning approaches[277,278] which do not require the *a priori* specification of the relationships between drivers and response variables, and can sometimes be employed within mechanistic frameworks[279]. In other situations, process-based models that ingest ground or remote sensing observations into predictive extrapolation frameworks are being used to map the present-day mitigation potentials of certain NbCS, for example in Maryland[108], New England[110], and the Southwest[280].

Earth system models (ESMs), which forecast future climate states for a range of anthropogenic emission scenarios, are currently the most robust tool for mechanistic prediction of climate–ecosystem feedbacks, and the only way to estimate the durability and net effect of combined physical and biogeochemical impacts into the future. The land-surface models embedded within ESMs come in many flavors[194], but they are generally constrained by fundamental conservation laws and rely on biogeochemical and biophysical theory to predict flows of carbon, water and other elements through the natural world[189]. However, with some exceptions[36,280], this class of models has not yet been widely applied to assess NbCS impacts, which may reflect that fact that these models are still limited in their capacity to represent management and disturbance processes, and in their skill at quantifying avoided emissions of non-CO_2 GHGs in agriculture. Moreover, future projections of land carbon uptake are very uncertain in ESMs, particularly into the latter half of the 21st century[281]. Put simply, the models do not agree on the magnitude, and in some cases the direction, of future land-carbon uptake at the global scale[282]. This fundamentally large and potentially irreducible uncertainty[283] poses major challenges for predicting NbCS permanence, and reducing it is a central theme in global change research.

4. A National Nature-based Climate Solutions Information Network

4.1. A network-enabled approach to closing the knowledge gaps

The knowledge gaps identified in the previous sections have many shared features. They highlight the need to **complement traditional stock-based estimates of carbon uptake with frameworks that harness ecosystem-scale carbon fluxes**, which integrate over many ecosystem carbon sources and sinks and that can quickly reveal the realized impacts of NbCS interventions. The solutions to the knowledge gaps emphasize **forward-looking and holistic assessments** of NbCS that (1) consider a full set of GHGs, (2) directly quantify the durability of carbon stored in soils and trees, and (3) consider the potential for NbCS to directly alter temperature and hydrologic cycling through biophysical impacts. Policy-relevant assessments of both the mitigation and adaptation potential of NbCS require **strategies for upscaling field- and farm-level assessments to landscape and regional scales**, so that NbCS programs can be designed with the knowledge of when and where NbCS strategies are most likely to succeed. Regardless of the policy instrument used to incentivize NbCS, all coordinated implementation programs will require **monitoring and validation protocols that are interoperable, rigorously benchmarked, and referenced to robust baselines** that are informed by the best-available science.

Coordinated investment in a national "NbCS Information Network" (would provide the data and derived products necessary to fully realize this vision, fostering robust NbCS strategies that work, and avoiding pursuit of NbCS strategies that don't work or might backfire. This new network could adopt a coordinated strategy for enhancing and expanding ground-based monitoring networks, integrating satellite data into scalable maps and models, and rigorously benchmarking protocols for project-scale accounting (Fig. 4). To be most useful, the network should be informed by centrally developed data protocols and best practices, supported by cyberinfrastructure for **transparent and interoperable sharing of data, code, and derived products**, and complemented by an information "service" to encourage product use by a wide range of end-users, and solicit user feedback on network needs and usefulness.

Fortunately, **the carbon cycle science research community has a long history of network-enabled information sharing.** Networks like the US Department of Energy's AmeriFlux network[66], NSF's National Ecological Observatory Network (NEON)[284], the USDA's FIA[68], NSF's Long-term Ecological Research (LTER)[285], and USDA's Long-Term Agricultural Research (LTAR)[286] programs are already providing valuable information about ecosystem carbon fluxes and stocks. Collectively, these networks span a gradient from: [1] coalition-driven, bottom-up networks (e.g., AmeriFlux, LTER, and LTAR) that collate site-level data generated by individual research teams working in universities, for NGOs, and for government agencies, to [2] more top-down networks like NEON and FIA, where all data is collected by staff from a single agency using centrally developed protocols. The top-down approach has the advantage of generating data that are highly standardized, freely available, and interoperable across sites, but these networks can take a long-time to build, and may lack flexibility in measurement design once established. The more *ad hoc* design of bottom-up networks means that data formats and measurement protocols may be inconsistent from one site to the next, which hinders synthesis; however, in contrast with tow-down networks, bottom-up coalitions tend to be nimble and capable of quickly responding to address novel questions[66].

Given the rapid pace at which NbCS programs are being developed and implemented, **the most efficient strategy will likely blend features of both top-down and coalitionary, bottom-up research networks.** For example, **measurement priorities and standards could be set centrally** through a process that solicits cross-sectoral expert input. Centralized investment in the cyberinfrastructure necessary to aggregate and deliver information to diverse end users is clearly necessary. Here, existing entities like the Carbon Cycle Interagency Working Group (CCIWG), the U.S. Carbon Cycle Science Program, the US Global Change Research Program, the North American Carbon Program (NACP) and other use-inspired and translational programs could play a central role. The NACP already facilitates the development of observation strategies and standards through community input, as demonstrated by the 2022 Science Implementation Plan and ongoing work by its Science Leadership Group. The CCIWG could leverage its Federal programmatic coordination to better enable cross-platform delivery of carbon cycle information at multiple scales.

A more bottom-up approach could be taken to the execution of field trials, monitoring campaigns, modeling studies, and protocol evaluations necessary to close the most pressing NbCS knowledge gaps; specifically, this work could be executed by consortia of research teams from many sectors (e.g. universities, NGOs, and government) through funding opportunities and cooperative agreements complemented with additional investment in network hubs to support the collection and standardization of data provided by individual teams. In this way, existing physical infrastructure (e.g., flux towers) and field experiments (e.g., from LTER, LTAR, etc.) could be more efficiently leveraged for information about the climate benefits of NbCS. Ultimately, delivery of information to a diverse array of end-users could be coordinated by a centralized body, emulating the model of existing programs for successful stakeholder engagement like the USDA Climate Hubs, the USGS Climate Adaptation Science Centers, and the NASA CMS Applications team (see Section 6 for more detail).

These interconnected research and outreach initiatives are described in more detail below. Particular attention will be paid to the knowledge gaps that each initiative could address and the timeframes over which progress could be enabled. **The biggest value of these activities is through their integrated and coordinated execution** – the whole is greater than the sum of the parts. The investment necessary to execute the research and development initiatives described in Table 1 is not small (~ $1 billion USD), though it is substantially less the tens of billions of federal dollars recently allocated for NbCS implementation. In any event, **the scope of the coordination required to develop a system like this should not preclude near-term investment in individual components of the system**. Indeed, investment in activities like new NbCS field trials, strategic enhancements to existing monitoring networks, mapping exercises, and systematic protocol and model intercomparisons would generate much needed information relevant to many of the knowledge gaps identified in this report. To every extent possible, however, this work should be guided by measurement and metadata standards that are strategically and centrally developed.
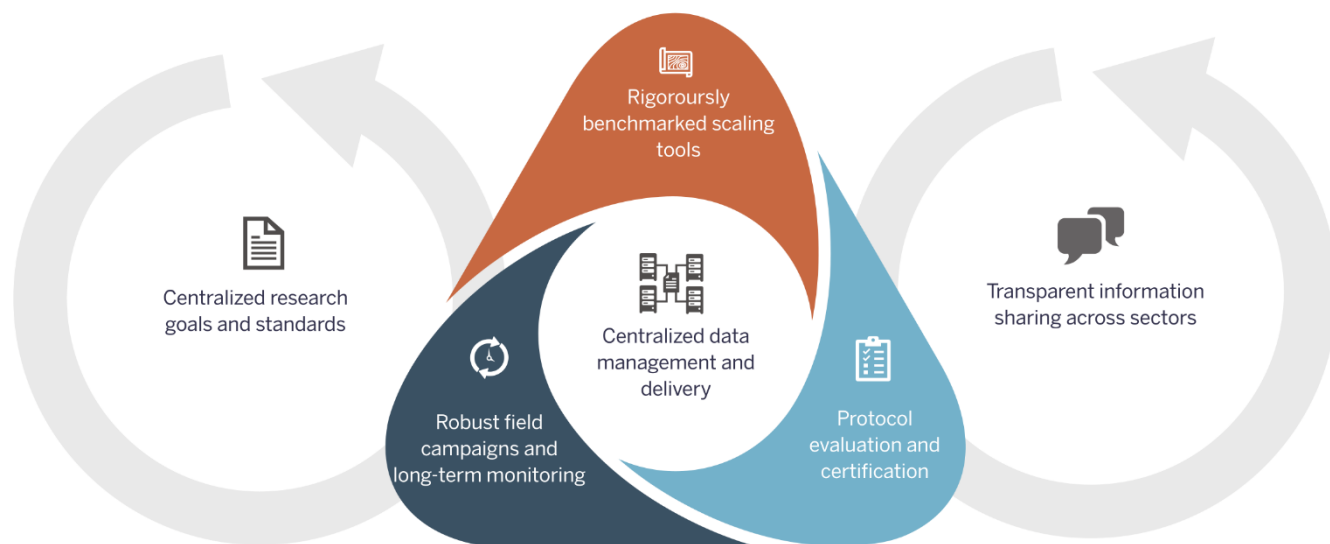
Figure 4: Core components of a National NbCS Information Network

4.2 A centralized task force for priority setting, data best practices, and data sharing

Providing actionable information to guide NbCS implementation depends on the timely, coordinated, and transparent delivery of interoperable field data and derived mapping and modeling products. Thus, there is a clear need for an interagency and cross-sectoral task force to identify the pressing data gaps, develop a set of best practices for robust ground monitoring, describe the metadata and other reporting requirements necessary for interoperable data systems, and to guide the development of cyberinfrastructure for information delivery. Given the diffuse sectors across which NbCS-relevant data are collected and used, **diverse perspectives are necessary,** representing expertise in carbon cycle science and policy implementation, and coming from university, government, NGO and private-sector settings.

Activities that could be guided by this task force include:

[1] A dynamic inventory of NbCS field trials and monitoring initiatives: A logical first step is a comprehensive inventory of what NbCS-relevant field data already exist, which could guide prioritization of new data collection. Other interagency, cross-sectoral initiatives like the Second State of Carbon Cycle Report (SOCCR2) have taken a necessary first step of collating general information about federally funded research programs that enable monitoring of carbon cycling. However, there is a need for much more granular information, including:

a) A dynamic catalog of both active and decommissioned field trials of NbCS interventions, including information on where the experiments were executed, what management strategies were applied, what categories of data were collected, and to which repository (if any) the data have been shared. A starting point could focus on federally funded research, but a more complete inventory would also include information about field experiments funded by NGOs or private organizations.

b) Documentation of the NbCS representativeness within long-term monitoring networks (e.g. AmeriFlux, NEON, LTER, LTAR, FIA). This documentation should focus on sites that are managed in alignment with NbCS strategies or relevant baseline controls. Metadata on climate, soils, management history, and stand characteristics (in the case of forests) would the identification specific gaps in the representativeness of our monitoring systems. For example, we may find that while mature deciduous forests are well-represented in networks like AmeriFlux and NEON, intermediate age stands necessary to complete successional chronosequences are largely absent.

This catalog could be created relatively quickly with adequate personnel support. Mechanisms allowing individual research teams to self-register and self-update would promote sustainability of the database, and could be incentivized by reporting requirements mandated by funding agencies.

[2] Centralized and community-crafted best practices for NbCS field data collection, curation, and sharing. In the next section, we will present a vision for the design of field trial campaigns and long-term monitoring initiatives to provide more robust and representative data for NbCS. However, the descriptions in this report should be viewed as rough sketches; the most effective implementation of coordinated field experiment and monitoring campaigns would be guided by community-developed best practices describing measurement protocols, sampling design, measurement frequency, and the collection of metadata necessary to facilitate scaling exercises and to allow data to be easily ingested into modeling frameworks. The task force could play an important role in formulating the standards, building from pre-existing models for protocol development from NEON (which are informed by the contributions of a wide range of scientists serving on technical working groups), and bottom-up coalitions like LTER and AmeriFlux (which has established clear templates for data reporting and sharing that facilitate rapid ingestion of flux tower data into post-processing pipelines[287]).

[3] Cyberinfrastructure for the coordinated and interoperable delivery of field data, remote sensing products, and derived products like maps, model forecasts, and code. Developing platforms to permit querying and acquisition of data that are extremely diverse with respect to scale, geography, and format seems daunting. The challenge is even greater if these data are to be delivered alongside derived products or codes that can easily be ingested into modeling frameworks. Indeed, **developing the cyberinfrastructure to enable the full potential of a national NbCS information network is a significant undertaking, and would require substantial investment of material resources**. However, it is not a task that must begin at square one. **The rich-history of network-enabled carbon cycle science research gives us many templates for coordinated data delivery systems.** These include the Environmental Data Initiative[288] and DataOne[289], which are searchable databases of ecological and environmental datasets shared by both individual principal investigators (PIs) and networks (including, for example, data generated from the LTER program). Other examples include: 1) the CMS Data Products Factsheet (a searchable database which lists and describes the metadata of diverse carbon datasets focusing on biomass, atmosphere flux, and oceans products), 2) existing systems for delivery of multi-scale biogeochemical data already supported through initiatives like the Oak Ridge National Laboratory Distributed Active Archive Center (DAAC[288]), and 3) the well developed data acquisition, processing, and delivery pipelines that already exist for networks like AmeriFlux and NEON.

A centralized task force could include a working group dedicated to bringing together data scientists from initiatives like these to scope the scale and structure of cyberinfrastructure investment necessary to support low-latency delivery of the NbCS-relevant data needed by a wide range of end-users. Moreover, this body could facilitate the outreach necessary to ensure effective use of these resources (e.g. the "information service"). The creation of the cyberinfrastructure systems could be executed directly by a federal agency or consortium, or through a competitive call for proposals following the model of the recent "Center for Advancement and Synthesis of Open Environmental Data and Sciences"[290] program sponsored by NSF.

Table 1: Summary of Centralized Initiatives. Refer to Box 2 for knowledge gaps. Costs represent rough estimates informed by publicly available information about the budgets of existing environmental observation networks, data science centers, and modeling and mapping initiatives. Interpretation of the icons is as follows.

Time frame
- Achievable on a rapid timeline (e.g., <1 year)
- Some aspects achievable immediately, but others may require more time
- Some aspects achievable within 2-3 year, while others may take longer

Cost (USD)
- $ = <10 million
- $$ = 10 - 50 million
- $$$ = 50 - 100 million
- $$$$ = >100 million

INITIATIVES	KNOWLEDGE GAP(S)	WHO	USE	TIME FRAME AND COSTS
Summary of Centralized Initiatives				
Dynamic inventory of NbCS field data	2.1a,b,c,d 2.2a,b,c 2.3a,b	Centralized task force	Guide design of new monitoring campaigns and network enhancements.	$
Best practices for data collection & sharing	Most gaps in Table 2	Centralized task force	Generate interoperable data features and reporting structures for synthesis, scaling, and model/ protocol benchmarking.	$
Cyberinfrastructure for coordinated NbCS information delivery	Most gaps in Table 2	New center or program (federal or university)	Deliver actionable information to a wide range of end users, for purposes including research and application purposes.	$$

4.3 Robust ground-based monitoring

Networks like AmeriFlux, NEON and FIA already contain a wealth of information that could be harnessed to address knowledge gaps identified in Section 2. Existing flux tower network data may already be sufficient for rigorous benchmarking of carbon cycle remote sensing products, at least for biomes that are well represented in these networks (e.g. temperate forests and grasslands). Also, some sites (e.g. NEON sites) already monitor a range of relevant data streams (e.g. tower measurements, carbon stock changes, near-surface remote sensing) for site-level evaluations of crediting and accounting protocols. However, many knowledge gaps cannot be comprehensively addressed without a dedicated commitment to collect more robust and representative data from sites that span gradients of climate, soils, vegetation types and management regimes (Table 2). In this section, we describe a coordinated set of field activities designed to generate this representative data and information. To a large extent, the material investment in developing these datasets and field campaigns could be reduced by leveraging existing physical infrastructure already in place within networks like AmeriFlux, NEON, LTAR, LTER, and the Advanced Research Projects Agency-Energy Program (US Department of Energy).

4.3.1 Gold-standard datasets: Standardized, robust, and comprehensive "gold-standard" datasets would be extremely useful for: [1] serving as a functional testbed to guide mechanistic understanding of the mitigation potential of emerging or understudied NCS strategies, [2] quantifying how NbCS activities affect fluxes and stocks not traditionally

considered in NbCS accounting (e.g. deep soil carbon, forest soil carbon, lateral export of carbon, and emissions of non-CO_2 GHGs), [3] understanding biases between data sources (e.g. carbon fluxes from towers versus stock change), and [4] serving as a validation dataset for accounting protocols, remote sensing products, and predictive models. The robust gold-standard datasets should enable **both flux-centric and stock-centric perspectives**, and include:

● **Ecosystem-scale flux tower measurements of carbon fluxes, methane fluxes, evapotranspiration, other energy balance fluxes**, and **a full suite of relevant meteorological drivers** (short- and long-wave radiation, soil and air temperature, relative humidity, and soil water availability at multiple depths).

● **Measurements of soil carbon stock change to a depth of 1 m, resampled every 1-3 years,** using soil cores and proximal soil sampling.

● **Annual measurements of the carbon contained in plant biomass** using allometric approaches for woody biomass informed by manual or automated dendrometer measurements, and destructive sampling approaches for herbaceous biomass including carbon exported from the system through harvest. Protocols for plant biomass sampling developed by FIA and NEON could be useful starting points for these measurements.

● **Measurements of soil nutrient pools, and their change in time,** coupled with rigorous documentation of nutrient additions (e.g., through fertilization).

● **Routine chamber-based measurements of non-CO_2 GHG emissions** (including methane and nitrous oxide), using automated chambers where possible and manual measurements elsewhere.

● **Measurement of carbon and nutrient losses through outflow and runoff,** where relevant (e.g. wetlands and tile-drained croplands).

● In forested ecosystems, automated or manual measurements of stem increment from dendrometers coupled with **representative sampling of tree cores**, to enable dynamic evaluation of stem growth responses to interannual climate variability (including historic variability).

● **Near surface (e.g., tower or drone-based) remote sensing information,** including SIF, hyperspectral reflectance, LIDAR, canopy temperature, and other emerging proxies for ecosystem structure and function, which are critical for bridging the gap between the sampling plots, tower footprints, and what we can see from space.

● Delivery of "**satellite remote sensing cut-outs**" which are pixel- or grid-specific time series of relevant proxies measured from space, in order to facilitate end-user access.

Especially useful datasets would emerge **from gold-standard paired-site campaigns** that feature sustained monitoring of a site managed with an NbCS "treatment" and a co-located baseline "control" which has historically experienced the same management regime. There is a long history of the use of paired experiments in ecosystem science, dating back to paired watershed experiments initiated in the early 20th century that profoundly advanced our understanding of how land management affects water quality and hydrology[291,292]. More recently, networks like LTER frequently support paired-site field-scale experiments to understand the consequences of different land cover and management practices on plant carbon uptake and growth[293]. Moreover, paired-sites experiencing different land cover/management but similar climate are prominent within networks like AmeriFlux[7]. Given the scarcity of NbCS field trials that report multi-scale (e.g. plot/plant to ecosystem to landscape) observations, **establishing a network of NbCS-oriented paired-sites to generate gold standard datasets is a clear research need.** These datasets would provide rich mechanistic detail on the holistic climate benefits of NCS strategies and also function as testbeds for the development of robust scaling tools, forward-looking models, and rigorous cross-comparison of crediting and accounting protocols. These data can also be interrogated for what they reveal about biases between flux-centric and stock-centric estimates of carbon uptake.

Creating **gold-standard datasets in long-term monitoring sites** also has value, even if done outside of a "paired-

site" setting. For example, pre-existing nodes of networks like AmeriFlux, NEON, LTER, and LTAR) could be augmented with the additional measurements necessary to complete the suite of "gold-standard measurements." Even without the benefit of an explicit treatment-control design, long-term datasets from individual sites would retain the promise of informing scaling tools and predictive models, by serving as ground-truthing data and/or as information that can be ingested into, or compared with, predictive modeling frameworks. Regardless of whether the gold-standard datasets are collected in paired or individual sites, they would be well suited for testing strategies to create accurate and dynamic baseline estimates.

To the extent that they can leverage pre-existing physical infrastructure, these paired sites could be established relatively quickly, and return actionable information on timescales of 1-3 years. Funding for these initiatives could be diffuse (e.g., coming from a wide range of federal, state, private, and foundation funding sources), though the collective benefit of the network would be strengthened by guidance on measurement protocols, frequency, and metadata standards developed by a centralized task force. **These gold standard datasets should be generated with the understanding that they will be shared freely and openly,** following the model of NEON and FIA and most sites within AmeriFlux that now adopt a CC-BY-4.0 data sharing license.

Figure 5: Gold standard datasets

4.3.2 Distributed and coordinated experiments and field trials. Gold-standard datasets would require substantial investment of time and resources, and thus would only be possible in a limited number of sites. Complimentary information could be obtained from distributed and coordinated experiments that include a more sites but a more limited number of observables. Coordinated field trials that target emerging or understudied NbCS (e.g. biochar, enhanced crop weathering, alley cropping, wetland restoration) are especially needed. Initiatives like the "Nutrient Network[294]" and the International Drought Experiment[295] can serve as very useful examples of how distributed campaigns can be implemented in a way that engenders diverse participation and impactful synthesis[296]. Both of these initiatives relied on a centralized group to describe measurement and experimental protocols for experiments that were then implemented by research groups working all over the world. Likewise, the extensive experience of scientists working at and across LTER, LTAR, and Critical Zone Collaborative Network (CZnet) sites, and associated investments in physical measurement infrastructure, could provide an important platform for implementing effective coordinated experiment campaigns[297].

4.3.3 Enhancing and expanding long-term flux monitoring networks. Substantial opportunity exists to enhance the representativeness of existing long-term monitoring platforms which report on at least a subset of the elements of gold-standard datasets. Doing so could provide critical, scalable information constraining baselines/counterfactuals, informing projections of risk/durability, and function as benchmarking tools for remote sensing products and model predictions. These opportunities include:

[1] Sustaining and expanding flux tower networks like AmeriFlux and NEON, so that they **better represent NbCS "treatments" and baseline "controls"**. Funding to sustain existing sites, and to expand representativeness of underrepresented ecosystems, could be executed centrally through existing network hubs (e.g. AmeriFlux, NEON) or through a more diffuse approach supporting individual research teams with the expectation that they will collect and openly share data using centrally-developed guidelines and formats. Particularly strategic expansions might include the deployment of tower systems at existing regeneration projects (of which there are over 1000 currently in the US[298], strategic investment in towers that measure non-CO_2 fluxes in croplands and wetlands[96], and investment in towers situated in young and intermediate age forests, which are generally underrepresented in the network. Any effort to expand the representativeness of flux tower networks would benefit from R&D to reduce the costs of flux tower instrumentation. **Providing "cut-outs" of satellite remote sensing proxies for both carbon stocks and fluxes for all AmeriFlux and NEON sites** is low hanging fruit that makes the remote sensing data more accessible to users that may be well-equipped to work with time series, but are not necessarily trained in the art of wrangling large geo-spatial datasets.

[2] Augmenting some existing flux tower sites with a subset of the variables represented in the gold-standard datasets, including routine monitoring of carbon stocks and non-CO_2 GHGs, tree-ring data, and near-surface remote sensing. These augmentations could be possible at a relatively low cost and would substantially enhance the robustness of these datasets. While many of these variables are already monitored at terrestrial NEON tower sites, though the protocols should be carefully evaluated for the extent to which they create datasets that are sufficiently spatially and temporally representative to provide NbCS-relevant understanding. Existing funding mechanisms, including the US Department of Energy Terrestrial Ecosystem Science program, the NEON Assignable Assets program and the NSF Macrosystems program, are good models for how to simultaneously augment the sampling design at existing flux tower sites; however, augmenting a sufficiently representative set of sites with additional measurements may require a relatively large investment of resources.

4.3.4 Enhancing forest inventory networks, including FIA. While FIA has successfully met a variety of stakeholder needs, the sampling protocols were not designed specifically with the goal of informing NbCS, as discussed extensively in Sections 2 and 3). Key limitations include: 1) long sampling intervals which make it difficult to attribute tree growth and mortality to disturbance events and interannual climate variability, 2) no routine monitoring of carbon in soils, litter, or dead wood pools, 3) limited information about mortality agents, 4) limited monitoring of small trees, and 5) the fact that a distributed plot network might not adequately capture the carbon cycle effects of patchy disturbances, particularly insect outbreaks and wildfire.

One particularly cost-effective opportunity to address several of these limitations is to collect increment cores during already scheduled visits of the forest plot network, to **create a spatio-temporal network of tree-ring data with annual-resolution information on tree growth.** A foundation of regional US tree-ring collections (totaling >50,000 samples) already exists in legacy collections[253], and the great majority of the cost of systematic tree-ring sampling is already committed through the routine FIA plot visits[253]. Increment cores are currently collected from at least one tree per plot to count rings in the field (for stand age) but the core is discarded on site. Modifying the sampling protocol to keep those cores, bring them into the lab, and process them into time series data would yield, over the course of the FIA's 5- to 10-year remeasurement cycle, a robust baseline. Even more valuable, in terms of disentangling confounded drivers of forest carbon dynamics, would be multi-cohort sampling in a subset of plots, as well as sampling of newly dead trees. Overall, adding tree ring sampling during planned visits to FIA plots would greatly enhance the program's capacity for monitoring, attribution, and forecasting[112,253,280].

Other opportunities include **augmenting protocols to more rigorously document the drivers of tree mortality** (especially important for improving durability predictions)**,** and **shortening the FIA sampling interval**

(e.g. to 5 instead of 7-10 years in the western US) or considering dynamic cycle lengths to improve attribution of tree growth to disturbance events and climate extremes. Better use of the data created by the national Forest Health Monitoring program, which includes aerial surveys of tree stress and mortality events of all kinds, along with ground-truthing visits, is another path to improve the estimation and attribution of landscape-scale tree mortality. Further, **augmenting a subset of FIA plots with routine monitoring of soil carbon, and carbon contained in standing dead wood and litter,** is a clear and high-priority research opportunity to increase the robustness of FIA data. Finally, a focus on **delivering FIA-based information about dynamic biomass stocks over larger spatial scales** (e.g. stand- to landscape), and leveraging remotely sensed data for interpolation, could go a long way for addressing fundamental scale gaps.

4.3.5 A national soil carbon monitoring network: Implementation of NbCS in managed agroecosystems has been slow[53], and there remains substantial uncertainty about the realizable and durable climate benefits of these strategies that can be traced to a lack of systematic understanding of the status of US soils (see Section 2). These considerations motivate the **clear need for a national soil carbon monitoring network[80]**. National-scale networks to monitor forest carbon stocks (e.g., FIA) and to monitor carbon fluxes (e.g., AmeriFlux, NEON) have already proven extremely valuable for understanding the mechanisms that drive variability in carbon cycling in space and time. However, **the absence of coordinated, long-term monitoring of the soil carbon pool represents a major gap in our ability to close ecosystem carbon budgets at policy-relevant scales**. It also limits application of the best-available science to the crediting and accounting protocols for agricultural soil carbon, which tend to rely strongly on changes in soil carbon stocks. Long-term soil carbon monitoring is a feature of many pre-existing networks, including NEON, LTER and CZnet[299] and new initiatives like the International Soil Carbon Network[300] and start-ups like Yardstick and Perennial are beginning the work of aggregating information on soil carbon into a centralized databases. However, the representativeness of soil carbon time series in these networks is quite limited, as they were not designed with the goal of capturing the broad gradients in climate, management, and geology. Major soil sampling initiatives in the US including the National Cooperative Soil Survey (NCSS), the USDA-NRCS Rapid Carbon Assessment (RaCA), and the USGS Geochemical Landscapes Program, on the other hand, were designed to sample across these gradients; however, these programs do not feature repeat measurements over time, and thus contain little information about the temporal dynamics of soil carbon.

The ideal design criteria of such a network include:

- **Statistically robust spatial representativeness**, covering a diversity of geographies, land use, and land management. Given that soil-based NbCS primarily involve working lands, cultivated and grazed land should be overrepresented in the survey design. Land use or land management pairs at each location would be particularly useful.

- Protocols should be **harmonized with any effort to add soil carbon sampling to FIA.**

- Sample plot design should be **harmonized with the resolution of available remotely sensed information about land cover** (e.g., 10 or 30 m^2)

- **Long-term commitment to resampling at regular intervals** (e.g., 3-5 years) and **to a depth of 1 m** or the bottom of the soil profile.

- The basic unit of analysis should include, **at a minimum, SOC, bulk density, gravel content and at least one basic physicochemical characterization** including texture, pH, cation exchange capacity, exchangeable cations and metals. For at least a subset of monitoring plots, particularly those on working lands, information on soil fertility, carbon fractions, isotopes and soil health indicators would benefit efforts to incorporate observations of SOC change into predictive modeling frameworks.

- **Well-developed metadata** reporting on the management activities of agricultural working lands. Long-term climate data and cut-outs of relevant remote sensing proxies would also benefit efforts to develop novel paradigms for scaling plot-level observations into wall-to-wall maps.

- To maximize cross-network synergies, an emphasis should be placed on **co-locating nodes of a new national soil monitoring network with the nodes of other networks already monitoring carbon stocks and fluxes** (e.g., FIA, AmeriFlux, NEON, LTER, LTAR), as well as colocation with other major federal land use and natural resource surveys (including the USDA-NRCS National Resources Inventory).

Ultimately, a network like this would provide critically needed baseline data against which the realized benefits of NbCS projects could be compared. It would also greatly expand the datasets that can be: 1) ingested into predictive models for calibration and validation, 2) used to benchmarking emerging approaches for remote sensing of soil carbon dynamics, and 3) used as functional testbed for next-generation approaches to monitor and verify the carbon benefits of individual NbCS projects.

Table 2: Summary of robust ground monitoring initiatives. Icons are the same as for Table 1.

INITIATIVES	KNOWLEDGE GAP(S)	WHO	USE	TIME FRAME AND COSTS
Summary of robust ground monitoring initiatives				
Gold-standard datasets in paired and long-term monitoring sites.	2.1a,c 2.2a,b,c 2.4a,b,c2.6a,b	Individual research teams working with existing network hubs, guided by centralized best practices.	Robust evaluation of emerging or understudied NbCS strategies. Rigorously compare and evaluate protocols for crediting & accounting. Benchmark remote sensing products and models Improve mechanistic understanding of NbCS. impacts and explore data biases.	⏱ $$$$
Distributed experiments and field trials	2.1a,b,c 2.2c 2.3a,b	Same as above	Replicated evaluation of emerging or understudied NbCS strategies. Permit benchmarking of models and remote sensing across broader gradients. Generate representative data required for potential mapping and dynamic baselines.	⏱ $$$
Enhancing flux tower networks (new sites, new ancillary measurements)	2.1a 2.2a,b,c 2.3a,b 2.4a,b,c	Same as above	Synthetic understanding of ecosystem-scale NbCS impacts (including biophysical impacts). Permit benchmarking of models and remote sensing across broader gradients. Generate representative data required for potential mapping and dynamic baselines.	⏱ $$$
Enhancing FIA (e.g. soil carbon, dead wood & litter, tree cores, mortality documentation, smaller trees, shorter resampling times)	2.1d 2.2a,b 2.3b 2.5a,b 2.6b	USDA Forest Service	Understand forest NbCS impacts on a more robust set of forest carbon pools. Improve attribution of growth and mortality to climate variability and disturbance processes Simultaneously enhance NbCS accounting. while supporting resilient forest management. Generate representative data required for potential mapping and dynamic baselines	⏱ $$$$
A new **national soil carbon monitoring network**	2.1,b,c 2.3a 2.5b,c 2.6a,b,c	USDA	Synthetic understanding of NbCS impacts on agricultural soils. Advance consensus on the realizable potential of NbCS in working lands. Monitor the durability of different soil C pool Generate representative data necessary for potential mapping and dynamic baselines	⏱ $$$$

4.4 Rigorously benchmarked scaling tools

4.4.1: Regional- and continental-scale mapping of NbCS mitigation potentials and biophysical impacts:

An understanding of when and where NbCS strategies are most likely to succeed is critical for designing successful implementation programs and policy. The ground-based monitoring plan described in the previous section, when combined with the growing set of information on ecosystem function from drone and spaceborne remote sensing platforms, paves the way for the next generation of tools for estimating NbCS potentials at policy-relevant scales.

The ecosystem-scale information provided by flux towers is especially well suited for benchmarking remote sensing products, which tend to provide information at ecosystem scales (e.g., pixel sizes of 0.01 to 1 km^2). Flux data informed by complementary measurements of carbon stock changes as part of gold-standard datasets would provide an unprecedented opportunity to validate remote sensing proxies of both ecosystem fluxes and stocks. Right now, flux tower data are rapidly being ingested into studies that seek to validate the usefulness of SIF (solar-induced fluorescence) and NIRv (near-infrared reflectance of vegetation) as proxies for photosynthesis[301,302], Vegetation Optical Depth (VOD) as a proxy for canopy water stress[303], and ECOSTRESS's land surface temperature changes as a proxy for ecosystem evapotranspiration[275]. However, data from platforms like these have not yet been widely applied to understand the impacts of NbCS-relevant land cover changes on carbon fluxes. **Harnessing information from "flux towers in the sky"[304] to understand and map the mitigation potentials of NbCS strategies is an especially timely research opportunity** that could be accelerated by broader accessibility and availability of near-surface remote sensing data (e.g. from gold-standard sites). This information could be used to bridge gaps in scale between flux tower footprints and the resolution of space-borne remote sensing platforms for ground-truthing. **Other opportunities include integrating data from the ground and/or remote sensing into predictive, mechanistic models** to extrapolate across time and space[110,280]. Model-based extrapolations have the advantage of robustly simulating expected changes in land-atmosphere fluxes and stocks, especially when they are applied using Bayesian approaches for ecological forecasting[305] that permit routine updating of model parameters as more data become available.

The next-generation remote sensing products also **afford novel opportunities to map the biophysical impacts of NbCS on energy and water cycling, at least at local scales**. New platforms like ECOSTRESS and Planet Lab satellites now provide proxies for land surface temperature and evapotranspiration at scales that are typically smaller than individual farms and forest. To the extent that the patterns of NbCS practice adoption are known (from remote sensing or ground observations), then **mapping the local biophysical impacts of these managed land cover and land use changes could be done relatively quickly.** For example, it should be relatively straightforward to blend maps of cover crop adoption with remotely sensed land-surface temperature or evapotranspiration to provide first-order estimates of the extent to which NbCS interventions affect temperature and water cycling at relatively fine scales. **Characterizing non-local biophysical impacts requires mechanistic climate model experiments[306]** to specifically probe the scales at which biophysical impacts from NbCS interventions add up to impact the climate system globally, while ensuring that model parameterizations are consistent with insights from gold-standard datasets.

4.4.2 Robust, dynamic baseline maps, at project- and policy-relevant scales:
The success of an individual NbCS project, or a scalable NbCS program, requires documentation that the intervention is driving a climatically-beneficial change relative to the business-as-usual baseline. As discussed earlier, most baseline estimates are generated using tools and approaches that were not designed specifically for this purpose. They do not account for interannual climate variability or long-term climate change, and do not take advantage of the best-available science for monitoring and predicting ecosystem carbon cycling across a range of scales.

In this subsection, we discuss opportunities for both flux-centric and stock-centric baseline mapping. In both cases, the algorithms used to enable the extrapolation of point- or stand-scale data to wall-to-wall maps could include: [1] traditional regression-based approaches relating changes in fluxes to mappable proxies, [2] machine-learning extrapolations which account for non-linear dynamics and do not require *a priori* assumptions about the relationships between fluxes, stocks, and their environmental drivers, and [3] the use of mechanistic models capable of ingesting data (e.g. through the Bayesian assimilation frameworks) into predictive spatial extrapolations.

Flux-centric baseline mapping: Provided carbon losses from lateral transfer or harvest are negligible or otherwise

accounted for, the net land-atmosphere flux of carbon is a robust proxy for carbon uptake that integrates over all ecosystem carbon pools. There are immediate opportunities to blend next-generation remote sensing proxies for both ecosystem structure and function with meteorological reanalysis products, and ground-based carbon cycle data to create dynamic baseline flux maps that can inform ex-post evaluation of the realized benefits of NbCS interventions. These approaches are already being used to create global maps of net carbon fluxes using flux tower data as inputs[278]. These existing products capture broad spatial patterns but lack are too coarse to function as NbCS baselines, and moreover lack the temporal resolution necessary to capture interannual variability[69]. As discussed elsewhere[7], there is an urgent need for upscaled flux maps informed by data from specific ecosystem types in specific regions (e.g. conventionally managed Corn Belt croplands or Eastern US deciduous forests). The temporal resolution of these maps could be as fine as monthly if informed by flux tower observations or satellite data with a sufficiently fast return interval. While flux-upscaling maps have not historically leveraged information on carbon stocks (e.g., from FIA, from a new soil monitoring network, or from remotely sensed information about aboveground biomass), machine learning algorithms are capable of ingesting these data alongside other data sources.

Finally, to the extent that representative time series are available within flux monitoring networks, the same approaches could be used to create upscaled flux maps of the net land-atmosphere exchange of non-CO_2 GHGs. The creation of FLUXNET-CH4 dataset – an open, global dataset of methane flux records from nearly 80 global methane sites – is an important first step in this direction[307]. A systematic effort to add methane flux measurements to NEON towers is a timely research opportunity.

While nitrous oxide observations are possible using flux towers, the analyzers necessary to generate them tend to be prohibitively expensive and require substantial infrastructure (e.g. temperature-controlled sheds and line-power). Only a small number of sites currently support tower-based nitrous oxide flux measurements[308]. Thus, with respect to nitrous oxide emissions, efforts to scale chamber-based flux measurements with mechanistic modeling may be a more efficient pathway for policy-relevant mapping of this GHG in the near term.

Stock-centric baseline mapping: While the net land-atmosphere fluxes of carbon and other GHGs offer a particularly robust perspective on the mitigation benefits of NbCS, the cost of installing and operating flux towers will always limit the spatial representativeness of these data. Thus, there is also a critical need for baseline mapping of carbon fluxes inferred from changes in carbon stocks, using remote-sensing information coupled with rigorous ground-truthing.

In the case of forests, wall-to-wall, dynamic forest biomass maps that are cross-comparable at relatively high spatial resolution could play an important role in baseline mapping, while also supporting leakage assessments and systematic evaluations of the protocols used to monitor and verify individual NbCS projects. Maps like these are likely possible already at a relatively coarse temporal resolution (5-10 years) that matches the sampling interval of FIA, building off protocols already developed (e.g. for NASA-CMS projects described in more detail in Section 3 and 6.1). Going beyond 'prototype' to 'operational' carbon cycle products that include sustained observations in a strategic, rather than opportunistic, program should be a priority. Opportunities for mapping forest biomass changes over shorter time periods would be supported by complementing FIA protocols with tree core sample and/or more frequent sampling schedules (see Section 4.3.4).

As discussed previously, an absence of representative data on soil carbon stock changes in working lands severely restricts our ability to map baselines relevant to most cropland NbCS (Section 2.1). The creation of a national soil carbon monitoring network (see Section 4.3.5) would be a critical step enabling robust wall-to-wall mapping of changes in SOC across US agricultural landscapes. Ideally these maps would consider not just total SOC, but also its structural form. To the extent that this network includes forest sites, or to the extent that FIA protocols are amended to include soil carbon monitoring, then mapping of changes in forest soil carbon would also be possible.

Figure 6: Integrating multi-scale data into robust, wall-to-wall mitigation potential and dynamic baseline maps.

4.4.3 Temporal scaling of durability and disturbance risks that incorporate multiple climate feedbacks:
At local to regional scales, efforts to account for the benefits and impacts of NbCS urgently need to grapple with permanence risks. Rigorous, science-based estimates of: 1) the absolute magnitude of permanence risks, 2) spatial patterns of these risks, and 3) how climate change will affect the temporal dynamics of these risks over the 21st century are crucial. Initial estimates of absolute magnitudes of historical risks and their spatial patterns can be derived from historical datasets, such as satellite data or forest inventory data. Subsequently, statistical models can be leveraged to project risks across the 21st century[30]. Many of the initiatives already described position us to **create wall-to-wall disturbance risk maps, particularly for forest ecosystems** (see Figure 7)**.** Mapping exercises like this would be supported by efforts to bridge the scale gap between inventory plots and remote sensing pixels, and by more informative documentation of the causes of mortality in FIA inventories. Datasets linking disturbance intensity to upscaled maps of above- and belowground carbon losses can then be used in remotely sensed estimates of disturbance reversal risks.

Figure 7. An example of statistically-modeled, historic relative risk maps for forest disturbance from fires, climate (e.g. drought) stress, and insect-driven mortality. From Anderegg et al. 2022[30], which also shows how these models can be used to predict future relative risks for different shared socioeconomic pathways.

Understanding the carbon cycle consequences of these disturbance risks requires continued investment in ecosystem model development to represent NbCS-relevant processes (including disturbance mechanisms) at relevant spatial and temporal scales. Gold-standard datasets, and improved representativeness of carbon cycle monitoring networks, would provide the information needed to pursue these research goals for a wide range of NbCS.

Table 3 - Summary of scaling initiatives, including potential and baseline mapping, and durability prediction. Icons are the same as for Table 1.

INITIATIVES	KNOWLEDGE GAP(S)	WHO	USE	TIME FRAME AND COSTS
Summary of scaling initiatives				
Regional-scale mapping of **NbCS potentials & expected biophysical impacts**	2.3a,b 2.4a,b,c	Individual research teams guided by centralized best practices.	Provide robust, policy-relevant information on where specific NbCS strategies are most likely to succeed as climate mitigation tools. Anticipate opportunities for climate adaptation, and avoid unintended biophysical consequences.	⏱ $$*
New approaches for **scalable, dynamic baseline maps** of net carbon fluxes	2.3a,b 2.5b 2.6a,b,c	Same as above	Develop robust, standardized and dynamic baseline flux maps against which realized benefits of NbCS can be compared; Potential to map non-CO_2 GHGs.	⏱ $$*
Wall-to-wall, dynamic, **high-res forest biomass and soil C maps.**	2.3a,b 2.5b 2.6a,b,c	Same as above	Baseline mapping, leakage detection, and protocol evaluation. Understanding the gap between technical and realizable mitigation potential.	⏱ $*
Wall-to-wall **forest disturbance risk maps**	2.5a,b,c 2.6c	Same as above	Understand spatial and temporal variability in durability risks associated with forest NbCS.	⏱ $$*
Improve model representation for NbCS management	2.5a,b,c 2.6c	Same as above	Enable robust, long-term forecasting of durability considering multiple climate feedbacks.	⏱ $$*

4.5 Protocol evaluation and certification

Regardless of the policy instrument used to incentivize NbCS, scalable and credible implementation of climate-positive ecosystem management will require strategies for monitoring and verifying the realized benefits of individual NbCS projects. The historical reliance on Voluntary Carbon Markets (VCMs) as the primary vehicle to incentivize NbCS, coupled with the wide array of private entities that comprise that VCM system, has resulted in an extreme diversity of project-scale accounting protocols with documented inconsistencies in how they measure and predict carbon uptake, non-CO_2 GHG emissions, additionality, leakage, and uncertainty. The extent of this diversity in approaches is so great that it is not at all clear that the climate benefits estimated using these protocols are equivalent or even comparable.

An **immediate research opportunity is** t**he systematic and centralized intercomparison of the accounting protocols currently used within VCMs and other incentivization programs** (e.g., SBTI-FLAG, REDD+).

Model-intercomparison projects (MIPs), which compare predictions from a variety of models driven by the same forcing data, have long been a hallmark of ecosystem carbon cycle research[309,310], but this approach has not yet been applied to the diversity of protocols available for project-scale NbCS accounting. **A particularly robust intercomparison would rely on data from the gold-standard NbCS datasets,** which would provide information on changes in both carbon fluxes and stocks. Eventually, whether or not a given protocol successfully estimates the gold-standard flux and stock changes (to some acceptable level of uncertainty) could represent a **credibility standard justifying use of the protocol in publicly supported, "climate-smart" certification programs**. In practice, this approach would be supported by the availability of adequate public information describing project-level activities and associated ecological impacts, to ensure that the protocols are robustly applied in practice.

Once gold-standard datasets have been created and shared, and assuming adequate public disclosures are available in private markets, protocol evaluation and certification could proceed relatively quickly. However, given that there would be a 1- to 3-year lag before gold-standard data become available, a useful first step could be a **NbCS protocol MIP that is organized around modeled estimates of the changes in ecosystem carbon stocks and fluxes** as opposed to actual data. In other words, this exercise would evaluate the extent to which the different protocols agree not only with each other, but also with predictions from ecosystem models that represent our state-of-the-art understanding of the biological mechanisms that drive changes in carbon cycling. This effort would need to account for the fact that many private market standards allow projects to use a wide variety of modeling and measurement techniques.

Outside of a formal intercomparison, other important opportunities exist to make carbon accounting protocols more robust, scalable and credible. A critical element of nearly all project-specific accounting schemes is their reliance on benchmarking realized benefits against a projected business-as-usual baseline to demonstrate **additionality**. As discussed already, these baselines tend to be generated using simple empirical models that were designed decades ago, long before accounting for the climate benefits of climate-smart management interventions was a clear information need or research goal. In the previous section, we discussed strategies for blending robust ground-based data with remote sensing scaling products to create baseline maps. **Quantifying the project-scale uncertainty associated with applying a regionally developed baseline is an important information need** that could be addressed quickly by leveraging existing, long-term observations of carbon stocks and fluxes from networks like AmeriFlux, NEON and FIA. To the extent that these regional maps perform as well as, or better than, traditional approaches, then unified, multi-scale baseline frameworks applicable from field- to regional-scales would represent important advances in the scalability of NbCS assessments.

Other opportunities exist **to create and evaluate approaches for generating project-scale dynamic baselines, for example through pairwise matching of project and control areas for program implementation**. This approach requires a reasoned basis for identifying reasonable control proxies. The ecological research community has substantial experience in designing and executing ecosystem- and landscape scale experimental manipulations (e.g., within LTER and LTAR). This experience may prove invaluable for establishing the standards for this "reasoned basis," especially when aided with information on soil type, macroclimate, species composition, and management history that should determine the degree of native similarity between a reference control and an NbCS treatment.

To the extent that they have a spatial resolution that matches that of NbCS projects (e.g., ecosystem or landscape scale), **dynamic baseline products may help to address the problem of adverse selection.** Specifically, baselines that more accurately represent the project-level ecology of a given project will minimize the opportunity for project developers to choose project sites that have higher native baseline carbon uptake (or lower emissions of non-GHGs emissions) when compared to regional baselines developed over much coarser spatial scales. **The data-driven and temporally dynamic baselines maps described in the previous section could also provide an important tool for quantifying leakage**, at least within the geographic boundaries for which they apply. For example, if lengthening of forest harvest rotations in one area of the country spurs more frequent harvesting elsewhere, this should be evident in the forest inventory data and the remote sensing information used to create the dynamic maps.

Looking forward, we can anticipate the development of new accounting and crediting protocols. For example, right now, the use of flux towers as a monitoring tool may not be feasible for all projects[113], but they may be an economically viable option for large and aggregated projects[7,311]. In the future, R&D to reduce to the cost of flux tower instruments, and to

explore the usefulness of short time series from "pop-up" tower deployments, may expand the suitability of flux towers as a monitoring tool for a wider range of NbCS projects. Remote sensing products, soil spectroscopy, and other state-of-the-art tools for sensing the carbon cycle impacts of NbCS are also likely to be incorporated into project-scale accounting protocols. **Gold-standard datasets and long-term network monitoring initiatives would provide the functional testbeds to assess new technologies and algorithms for project-scale accounting,** and for evaluating whether emerging approaches agree or disagree with more traditional methods.

Finally, it should be reiterated that the failure of most project-scale accounting protocols to robustly quantify and value the durability of climate benefits is a major gap that should be addressed as quickly as possible. The most rigorous attempts to project the permanence of the climate benefits of a given NbCS project would rely on mechanistic models coupled with dynamic forcings that accommodate the potential for a wide range of climate feedbacks. Right now, this is a computationally expensive proposition requiring specialized programming expertise that may be possible within well-supported research projects, but is not currently scalable to for broad application to NbCS. **With continued research and development investment in ecological forecasting initiatives[305] and other programs designed to reduce the accessibility burden for predictive, mechanistic modeling, these tools may become more accessible and scalable.**

In the meanwhile, **durability can be addressed, in part, through robust eligibility criteria.** Many carbon programs attempt to be broadly inclusive with respect to eligible practices and geographies. To the extent durability risks or biophysical impacts vary substantially across practice or geography, it might make more sense to exclude practices where durability risks are high or biophysical impacts are negative. An even more conservative approach would be to limit eligibility to practices or geographies where durability risks are low. These exclusion criteria could be governed by the disturbance risk maps described in the previous section.

Table 4 - Summary of protocol evaluation and certification initiatives. Icons are as in Table 1.

INITIATIVES	KNOWLEDGE GAP(S)	WHO	USE	TIME FRAME AND COSTS
Summary of protocol evaluation and certification initiatives				
Systematic cross-comparison of protocols for project-scale crediting, monitoring, and verification	2.6a	Individual research teams working closely with federal and private stakeholders	Understand the extent to which carbon credits are interoperable. Provide a mechanism for certifying climate-smart commodities. Increase trust in NbCS incentivization programs.	⏱ $$*
Evaluate approaches for **implementing dynamic baselines** in protocols	2.5a 2.6a,b,c	Same as above	Develop approaches to additionality evaluation that are scalable, reduce bias, and minimize risks of adverse selection and over- or under-crediting.	⏱ $$*
Make predictive models more accessible to non-experts	2.5c 2.6a,b,c	Same as above	Inform the development of NbCS incentivization programs that favor strategies in the places they are most likely to succeed.	⏱ $$*

5. Contending with Uncertainty

Developing consensus around acceptable levels of uncertainty is a multi-pronged challenge. First, at a high level, the scientific community (including the participants in this workshop) certainly have not reached consensus on the realizable climate benefits of NbCS and on how aggressively they should be pursued. Questions remain about the true potential for real, durable, additional, net-cooling, and leakage-adjusted NbCS. The information network described in this report represents a pathway towards closing many of the knowledge gaps that currently hinder such a consensus. While useful information from these measurement systems and prediction tools could become available within the next 1-3 years, we acknowledge that NbCS policy and program design is evolving very rapidly.

Thus, in the near term, when thinking about how to design NbCS incentivization programs, it may be useful to focus on areas where consensus does exist. First and foremost, the participants in this workshop that motivated this report unanimously acknowledge that the most effective climate mitigation tools are those that reduce emissions of greenhouse gasses from fossil fuel burning. While NbCS can provide important additional mitigation, **NbCS cannot be successful if they are not pursued concurrently with economy-wide decarbonization**. Next, there is broad-scale agreement that the adoption of **many categories of NbCS benefit landowners and the environment through co-benefits** linked to soil health, biodiversity, and air and water quality. There is agreement that we should push to incentivize those practices using a wide range of tools based on this holistic set of benefits but be careful about their promotion as climate solutions where this potential is not well constrained. There was also broad-scale agreement that **GHG emissions reductions (versus removals) are critical components of robust NbCS for agricultural and wetland systems**; however, the voluntary market and corporate climate commitments have catalyzed an emphasis on removals over reductions. Finally, there was strong agreement among participants in the workshop that **accounting challenges and durability of carbon sequestration create significant risks for using any generated credits as offsets** for anthropogenic emissions. This set of challenges underscores the idea that the timescale of sequestration should match the lifetime and source of the emissions the credits are intended to offset.

The second prong of uncertainty is more quantitative. It includes uncertainty in carbon stock and flux measurements, and challenges related to propagating that uncertainty into scalable mapping tools and predictions of the durability of NbCS benefits. Identifying, quantifying, and combining (i.e., propagating) the various sources of measurement and modeling uncertainty is an essential ingredient of robust estimates on how NbCS impact carbon stocks and fluxes, now and into the future. This information can also be used to prioritize efforts to refine and improve sampling, analysis, and modeling approaches. **A recurring theme throughout this report concerns the critical role of data representativeness in constraining uncertainty**. Other sources of uncertainty in assessment of carbon stocks and fluxes include instrument error, sampling errors due to improper plot size or number of samples, and uncertainty linked to the algorithms used in data screening and quality control. Fortunately, ecosystem ecologists have a long history of leveraging network datasets, which often encompass a wide range of measurement protocols, into **standardized synthesis products that explicitly account for measurement and sampling uncertainty** that can be readily propagated through into modeling frameworks[67,287].

Broadly, NbCS initiatives and projects could be based on guidelines established by the Intergovernmental Panel on Climate Change (IPCC) for quantifying and propagating uncertainty in greenhouse gas inventories, which includes guidance on how to incorporate expert knowledge. The IPCC guidelines are divided into three hierarchical tiers of increasing methodological complexity and increasing levels of accuracy assessment. Tier 1 is a simple first order approach characterized by large uncertainties and a simple approach to error propagation with a set of basic assumptions about error structure. Tiers 2 and 3 involve a more rigorous approach to uncertainty assessment, including comparisons of estimates across multiple approaches and observations, as well as a more sophisticated Monte Carlo approach to error propagation with fewer simplifying assumptions. Ideally, NbCS projects and initiatives would abide by Tier 2 guidelines at minimum, which is not the case at present. However, the integrated set of monitoring, scaling and modeling activities described in Section 4 could pave the way for more rigorous quantification of uncertainty across multiple scales relevant to NbCS program design and implementation.

None of the sources of uncertainty described in this report can be constrained and quantified in the absence of open, accessible data. The information network described herein assumes that all NbCS-relevant data supported by federal investment will be made freely available, discoverable, and usable through centralized cyber-infrastructure and data delivery systems. However, given the central role that the private sector has played and will continue to play in driving NbCS implementation, there is a clear need to demand transparency on accounting for any credits that are generated and verified. **Verification documents should be publicly available with sufficient detail to understand the estimated uncertainties and how they were quantified,** as well as documentation that enables transparent and reproducible use of the models deployed to estimate GHGs.

6. Beyond Technical Potential: Cross-sectoral Engagement, Socio-economic Considerations, and Equitable Implementation

Maximizing NbCS effectiveness in the real world requires end-to-end engagement of practitioners, federal and local government agencies, NGOs, carbon market players (e.g., corporations, registries) and other actors deeply connected with the implementation of NbCS programs and policies. Effective NbCS programs will also require substantial research and development investment to understand the socio-economic factors that determine the gap between technical and realizable mitigation potentials. Effective and equitable NbCS programs will also require strategies to sustain and reward early adopters of NbCS practices, and to ensure that NbCS strategies are accessible and advantageous to diverse communities. Fully characterizing the relevant knowledge gaps for these critical design components, and describing strategies to overcome them, is beyond the scope of this report. Nonetheless, here, we discuss some particularly pressing needs and opportunities.

6.1 End-to-end stakeholder engagement and the delivery of analysis-ready data products.

The data, information, and technology resources described in this report will only be useful if they are paired with thoughtful strategies for cross-sectoral engagement. A strategic "information service" that briefs interested parties on the availability of data products, provides training on cyberinfrastructure access, and develops coordinated cross-sectoral outreach strategies will be critical for permitting the realizable potential of NbCS to be as close as possible to the technical mitigation potential.

Several existing programs provide templates for how to accomplish strategic scoping, outreach, and product delivery. For example, the NASA-CMS program, initiated in 2010 by Congressional direction, supports high-resolution carbon data products developed through extensive stakeholder engagement. The CMS Applications Program Framework, which functions as a bridge between scientific and end-user communities, moves research outputs into products that can be used for decision support and to provide societal benefits. This engagement is achieved through a series of activities including lecture series, stakeholder workshops, data tutorials/trainings, a data products fact sheet, a product maturity index, surveys/community assessments, and socioeconomic studies. Successful case studies supported by the CMS program include: [1] engagement with the Maryland Department of Natural Resources to develop high-resolution forest carbon maps to inform the state's forestry and sequestration sector, and to support forest preservation efforts, [2] the NASA-USFS Partnership to Advance Operational Forest Carbon Monitoring in Interior Alaska, which uses the NASA G-LiHT instrument to systematically inventory forests in a region which encompasses 15% of US total forest land but which is not included in the FIA Program, and [3] an effort to develop maps of mangrove forest distribution and structure which are being used by NGOs such as The Nature Conservancy to integrate the data into the Global Mangrove Watch platform (see the CMS website[312] for more details).

Another model is the USDA Climate Hubs[313], a unique cross agency program that bridges research and program agencies supporting climate-smart adaptation, mitigation, and resilience on America's working lands. The Climate Hubs develop and deliver science-based, region-specific information and technologies for agricultural and natural resource managers to support climate-informed decisions, minimize risks, and build climate resilience. The Hubs work with trusted community partners including cooperative extension, universities, and others to deliver climate-smart solutions to USDA's stakeholders including farmers, foresters, Indigenous peoples, and other land stewards. Specific Hub syntheses, tools, and stakeholder processes include: regional climate vulnerability and risk assessments that highlight adaptation and mitigation opportunities; AgRisk Viewer -- a web-platform that provides discoverable and accessible crop insurance loss data; and peer-to-peer learning networks such as the Drought Learning Network and Climate Adaptation Fellowship program. The Hubs are the premiere model for climate information services in agriculture and forestry through stakeholder engagement and knowledge co-production, and may serve as the foundation for further knowledge, application, and adoption of NbCS, many of which may also be considered climate-smart agriculture and forestry practices.

6.2 Engagement with state governments and Tribal leaders

While the NbCS information network described in Section 4 is imagined as a federal initiative, more local programs and policies are nonetheless foundational for scalable and equitable adoption of NbCS in the United States. State-level programs and policies may be particularly well positioned to address issues like workforce development, infrastructure capacity, and technical assistance that are critical for widespread implementation of NbCS and are not fully addressed in this report. One example of a state program that is addressing these barriers and encouraging the adoption of healthy soils practices in Colorado is the Saving Tomorrow's Agricultural Resources (STAR)[314] and STAR Plus Pilot Program (launched in 2022). Through the STAR Plus Program, conservation districts can provide incentive payments and technical assistance to enrolled producers. The program also includes a research component: funding from a NRCS Conservation Innovation Grant (CIG) is being used to support research on the socioeconomic barriers to the adoption of soil health practices. Another example is the State of Maryland's "Plan for Growing 5 million Trees"[315] which seeks to advance assistance to rural and urban communities, to increase the state's seedling stock, to establish a common monitoring and verification system, and to develop strategies for long-term tree maintenance and management. New programs and policies should similarly leverage existing efforts where possible—such as conservation districts, extension agents, and academic institutions—to fortify and enhance long-standing, place-based expertise and relationships to increase the pace and scale of NbCS adoption. Development of "model policies" that could help accelerate the pace and scale of NbCS adoption would be beneficial as a template for states and local entities interested in pursuing NbCS. Model policies would help states better prioritize investment in applicable NbCS pathways, as well as better understand how NbCS could contribute to state and national climate goals.

Bi-directional engagement with Indigenous people is also foundational for NbCS to succeed[316]. In the United States, Indigenous tribes currently manage ~120 million acres of land[317]. Prior to European colonization of what is now the US, Indigenous peoples were stewards to much larger land areas, with many tribes using tools like selective harvesting and prescribed fire to sustain biodiverse and productive landscapes, including forests and tallgrass prairies[318-320]. During and after colonization and the forced displacement of Indigenous tribes, widespread land clearing for agriculture and timber, followed by extensive fire suppression in the 20th century, have set the stage for catastrophic wildfires and profound forest species composition shifts that we are now witnessing today[28,320]. Several studies highlight the value of Indigenous knowledge for crafting sustainable land management practices, including to guide NbCS[58,316]. For example, as discussed in detail in Fleischman et al. (2021)[321], the Yurok Tribe of Northern California successfully leveraged funding from the California Air Resources Board offset market to acquire a substantial holding of private timberland located within their ancestral homeland, with the goal of restoring traditional landscapes and re-establishing management practices (including fire management). However, in other situations, carbon offset programs have been criticized for excluding Indigenous groups for a variety of reasons, including the fact that lands managed sustainably by Indigenous stewards may not meet the criteria for additionality[316]. In general, policies and programs used to implement NbCS will be most effective when they are developed in consultation with Tribal leaders and Indigenous networks to ensure that strategies protect Indigenous rights and do not further disadvantage Indigenous communities[8,316,322,323].

6.3 Socio-economic factors challenging widespread and equitable adoption of NbCS

There remain logistical, cultural, data, economic, and educational gaps that create a disconnect between the urgent need for climate change mitigation and speed with which NbCS practices are being adopted. In many cases, land managers have fine-tuned the practices they use over generations such that lands remain productive, profitable, and safe guarded against climatic and biological threats. While a change in land management practice might be shown to increase carbon uptake and produce co-benefits at regional or global scales, such changes still embody a certain amount of risk at the field scale. To increase land manager confidence in NbCS practice assimilation, **networked observations of the physical impacts of NbCS on working lands could be complemented with information about residual effects that are relevant to producer livelihoods**, including quantitative information about yield, fertilizer application, and irrigation, as well as qualitative information about the factors that determine landowner practice adoption and abandonment. Moreover, because monitoring, reporting and verifications costs tend to predominate the

overall cost for implementation of most NbCS, it is important that emerging protocols either keep these costs stable or lead to increased sale prices that can compensate for the increased cost of monitoring and verification.

Successful implementation of NbCS will also require **dedicated education and outreach to individual landowners** who, even if they are generally interested in adopting NbCS practices, will have to overcome significant logistical hurdles. For instance, for a producer interested in applying a climate-smart soil amendment (e.g., compost, silicate-rock dust), questions about sourcing, application, and cost may all pose uncertainties that are challenging to reconcile. Moreover, landowner participation in programs like voluntary or compliance carbon markets typically requires the implementation of obscure and complicated accounting protocols, typically through contracts with project developers that are prohibitively expensive for owners of farms or forest stands that are relatively small in size. Existing programs like the USDA Climate Hubs network or land-grant university extension programs could serve as models for scalable outreach that connects practitioners with the best available NbCS information and resources.

Increasing **equitable access and implementation of NbCS** through co-production, community engagement, and trust building may also increase the likelihood of NbCS success by making these approaches more relevant and desirable to previously underserved communities[324]. A useful model for equitable engagement is Justice 40[325] – a whole-of-government effort that aims to deliver at least 40% of overall benefits from Federal investments in climate and clean energy to disadvantaged communities. These include rural and Tribal communities who are disproportionately impacted by climate change impacts, while also being the primary stewards of the Nation's natural resources that support agriculture and forestry sectors. Equitable implementation of NbCS would maximize climate change benefits while also promoting environmental justice and supporting underserved communities. Especially with the Climate Hubs, there are both opportunities and resource gaps in truly delivering on equitable implementation of climate-smart agriculture and forestry and NbCS. For example, there may be opportunities to use the Climate Hub's tools and technologies to understand "cold spots" in delivery of USDA programs and resources, and develop regional syntheses of how NbCS and climate-smart agriculture may positively affect these underserved communities in building climate resilience and sustainable development.

At broader scales, widespread implementation of NbCS is also associated with **substantial scaling challenges related to resource availability**. Using the example of compost and silicate rock dust again, while there may be enough resources to scale these NbCS practices in theory, access to these resources is currently limited without adequate scaling of the technology. The availability of seeds for cover crops is another potentially limiting factor. These barriers will likely requir**e private-public partnerships to ensure the accessibility and affordability of material resources** necessary to rapidly increase NbCS practice adoption.

Other macro-scale economic dynamics and feedbacks will determine the effectiveness of NbCS initiatives, and in particular leakage. Leakage will likely be most problematic for NbCS practices that substantially affect harvestable yield in working lands (e.g., altered forest management) or that drive a large price differential between commodities produced with "climate-friendly" practices versus more traditional management. The peer-reviewed literature on NbCS leakage is scant and represents an urgent research priority. Another example requires a global perspective; while this report is largely focused on implementation of NbCS in the United States, other nations are also implementing NbCS as part of their overall climate mitigation strategies. To the extent that land-sector climate policy elsewhere affects the price of carbon or the supply/demand for NbCS relevant commodities, then these macro-scale forcings may feedback to determine the financial feasibility of specific NbCS in the U.S. **Strategies for updating the physical mechanisms in economic models, and/or for incorporating natural resource economic drivers into earth systems models, is a challenging but important direction for future research.**

7. Summary

Addressing the climate crisis is fundamental for the national interest. More frequent and intense wildfires, droughts, floods, and heatwaves are already posing grave and interconnected threats to agriculture, human health, biodiversity, and physical infrastructure. Scientists and societal leaders agree that limiting the global temperature increase to well below 1.5 °C is fundamental for preventing dangerous tipping points that will damage our natural and built environment, economic growth, and societal well-being. There is still time to meet these targets, but success depends on bold and collaborative leadership grounded in the best-available science.

Ultimately, stopping and reversing climate change hinges on reducing and eliminating anthropogenic emissions of greenhouse gases (GHGs) from fossil fuel burning. However, in the near term, complementary approaches for removing CO_2 directly from the atmosphere will likely prove necessary to prevent dangerously high levels of warming. One way to do this is by land-based "Nature-based Climate Solutions" (or NbCS), which are a range of management strategies for croplands, grasslands, forests and terrestrial wetlands designed to increase CO_2 sequestration from the atmosphere or to reduce ecosystem emissions of non-CO_2 GHGs like methane and nitrous oxide. NbCS confer well-known environmental co-benefits for biodiversity, air and water quality, and soil health, in addition to essential economic benefits for farmers, foresters, Indigenous peoples, and other stewards of working lands. NbCS can also enhance the resilience of landscapes to threats exacerbated by a changing climate – such as drought, floods, wildfires, invasive species, and pests.

NbCS are receiving increased attention from a unique coalition of actors, including bipartisan lawmakers, conservation groups, the private sector, and many federal and state agencies. In the first 8 months of 2022 alone, tens of billions of U.S. federal dollars have been allocated for their implementation, and private sector participation in carbon offset markets that trade in NbCS credits have experienced rapid growth. Given this momentum, NbCS will likely be a core feature of domestic climate mitigation strategies moving forward. While there is ample justification for implementing NbCS on the basis of their co-benefits alone, for NbCS to succeed specifically as climate mitigation tools, they must accomplish **four essential functions:** [1] lead to enhancements of carbon uptake and/or reductions of GHG emissions **that are additional** to what would have occurred in a baseline scenario, and **that consider all the potential sources and sinks**, [2] lead **net cooling** considering biophysical impacts on water and energy cycling, [3] achieve **durable** carbon storage and emissions reductions, and [4] account for **leakage**.

Right now, **the extent to which NbCS meet these key criteria is highly uncertain**. At regional and national scales most relevant to policy-setting, estimates of the present-day mitigation potentials of NbCS vary widely from one study to the next. These potentials are usually estimated by focusing on a narrow set of soil and tree carbon pools that can over- or under-estimate ecosystem-scale carbon storage, and which do not reveal much about non-CO_2 GHGs or biophysical impacts on water and energy cycling. For many NbCS, the existing data are sparse and unrepresentative of naturally occurring variability in working lands. The durability of carbon stored in soils and trees, as well as the leakage potential, are difficult to quantify and are not robustly considered in NbCS accounting schemes. Finally, current protocols used to monitor and verify the benefits of individual NbCS projects vary widely from one entity to the next and lack systematic standardization across common data sets.

Fortunately, substantial opportunity exists to address this uncertainty. The crucial role that terrestrial ecosystems play in determining atmospheric CO_2 concentrations is well-established, and huge resource investments over decades have fostered innovative measurement technologies, analytical tools, and predictive models for quantifying ecosystem carbon cycles. These tools have historically been used for basic research and are not widely leveraged for what they reveal 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, but most have not yet been widely deployed. Thus, right now, **we have a unique opportunity to integrate the best-available science into next-generation information systems to support effective NbCS programs and policies.**

In recognition of this opportunity, in June of 2022, a cross-sectoral group of academic, federal and NGO scientists, program managers and practitioners came together to evaluate **the science, data, and information necessary to**

support <u>robust, scalable, and credible</u> **NbCS strategies for the U.S** (Box 1). This report emerges from that workshop, identifying key knowledge gaps (Section 2), and providing a roadmap for **actionable, cross-sectoral information to foster NbCS strategies that work,** and to avoid wasting energy and resources on those that do not. **Coordinated investment in a national NbCS "Information Network"** (Section 4) organized around strategic leveraging of existing research infrastructure, would provide the data and derived products necessary to close these knowledge gaps, ultimately fostering robust, scalable and credible NbCS strategies. are summarized in Table 5 below.

Table 5: Summary of recommended activities for a national NbCS "Information Network."

Create a centralized, cross-sector NbCS task force

- Inventory existing data
- Identify data and information gaps
- Define best practices for measurement and data sharing
- Guide the development of cyber-infrastructure to make data, maps, and code openly available and usable by a wide range of stakeholders

Enhance and expand ground-based monitoring networks and distributed experiments

- Create robust gold-standard datasets against which models, mapping tools and monitoring protocols can be evaluated and compared
- Create networks of distributed field trials and experiments to evaluate emerging or understudied NbCS strategies
- Enhance existing environmental observation networks with more representative sites and/or data
- Create a national soil carbon monitoring network

Develop rigorously benchmarked maps and scaling tools

- Facilitate regional-scale mapping of NbCS mitigation potentials and biophysical impacts on temperature and water cycling
- Support new approaches for mapping baselines that are dynamic in time and can be regularly updated
- Create dynamic, wall-to-wall maps of forest biomass, soil carbon, and disturbance risk
- Improve model representation of NbCS management strategies

Create credible protocols and certification strategies

- Support systematic cross-comparison of protocols for project-scale crediting, monitoring and/or verification
- Evaluate approaches for implementing dynamic baselines in project-scale accounting schemes
- Make predictive models and other tools more accessible to non-experts

The biggest value of the network activities is through their integrated and coordinated execution – the whole is greater than the sum of the parts. The investment necessary to fully realize this vision is not small (~$1 billion USD), though it is substantially less than tens of billions of dollars recently allocated for NbCS implementation. In any event**, the scope of the coordination and investment required to develop a network like this should not preclude near-term investment in individual components of the system,** which would generate much needed information relevant to many of the most pressing knowledge gaps.

This network would largely create information needed to assess and quantify the technical mitigation potential of NbCS. Socio-economic factors can cause the "realizable" potential to be lower than this upper-bound maximum. Research on the socio-economic factors that determine landowner decision-making, coupled with bidirectional outreach and education between scientists and stakeholders, are critical elements of successful NbCS programs. Moreover, while this report presents a vision for a federal network, state governments and the private sector undoubtedly have major roles to play in the development and implementation of more robust NbCS strategies. Successful and sustained cross-sectoral and cross-scale engagement is crucial.

Bibliography

1   Walker, X. *et al.* Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* 572, 520-523 (2019).

2   Jay, A., *et al. Overview.* In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 33–71. doi: 10.7930/NCA4.2018.CH1 (2018).

3   Kogo, B. K., Kumar, L., Koech, R. Climate change and variability in Kenya: a review of impacts on agriculture and food security. *Environment, Development and Sustainability* 23, 23-43 (2021).

4   IPCC, 2022: Summary for Policymakers [Pörtner, H.-O. et al. (eds.)]. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Pörtner, H.-O. *et al.* (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001. (2022)

5   Hartmann, H. *et al.* Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology* 73, 673-702 (2022).

6   National Academies of Sciences, Engineering, and Medicine (NASEM). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259. (2019).

7   Novick, K. A. *et al.* Informing Nature-based Climate Solutions for the United States with the best-available science. *Global Change Biology* 28, 3778-3794, doi:10.1111/gcb.16156 (2022).

8   Fleischman, F. *et al.* Pitfalls of tree planting show why we need people-centered natural climate solutions. *BioScience* 70, 947-950 (2020).

9   Nolan, C. J., Field, C. B., Mach, K. J. Constraints and enablers for increasing carbon storage in the terrestrial biosphere. *Nature Reviews Earth and Environment* 2, 436-446 (2021).

10   Seddon, N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science* 376, 1410-1416 (2022).

11   Matthews, H. D. *et al.* Temporary nature-based carbon removal can lower peak warming in a well-below 2° C scenario. *Communications Earth & Environment* 3, 1-8 (2022).

12   IPCC. Summary for Policymakers. 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* [Masson-Delmotte, V. *et al.* (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24, doi:10.1017/9781009157940.001. (2018)

13   Houghton, R. A. Terrestrial fluxes of carbon in GCP carbon budgets. *Global Change Biology* 26, 3006-3014 (2020).

14   Keenan, T. F. & Williams, C. A. The terrestrial carbon sink. In *Annual Review of Environment and Resources* (Gadgil, A. & Tomich, T.P. *eds.*) 43, 219-243 (2018).

15   Friedlingstein, P. *et al.* Global carbon budget 2021. *Earth System Science Data* 14, 1917-2005 (2022).

16   Keenan, T. F. *et al.* Recent pause in the growth rate of atmospheric CO2 due to enhanced terrestrial carbon uptake. *Nature Communications* 7, 1-10 (2016).

17   Lloyd, J. Current perspectives on the terrestrial carbon cycle. *Tellus B* 51, 336-342 (1999).

18   Walker, A. P. *et al.* Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. *New Phytologist* 229, 2413-2445 (2021).

19   IPCC. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., *et al.* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001. (2021)

20   Odum, E. P. The Strategy of Ecosystem Development: An understanding of ecological succession provides a basis for resolving man's conflict with nature. *Science* 164, 262-270 (1969).

21   Novick, K. A. *et al.* On the difference in the net ecosystem exchange of CO 2 between deciduous and evergreen forests in the southeastern United States. *Global Change Biology* 21, 827-842 (2015).

22   Curtis, P. S. & Gough, C. M. Forest aging, disturbance and the carbon cycle. *New Phytologist* 219, 1188-1193 (2018).

23   Paw U, K. T. *et al.* Carbon dioxide exchange between an old-growth forest and the atmosphere. *Ecosystems* 7, 513-524 (2004).

24   Hudiburg, T. *et al.* Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. *Ecological Applications* 19, 163-180 (2009).

25   Xiao, J. *et al.* Assessing net ecosystem carbon exchange of US terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agricultural and Forest Meteorology* 151, 60-69 (2011).

26   Domke, G. *et al.* in *In Second State of the Carbon Cycle Report : A Sustained Assessment Report.*   (eds N. Cavallaro *et al.*) 365-398. US Global Change Research Program (2018).

27   McKinley, D. C. *et al.* A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications* 21, 1902-1924 (2011).

28   Novick, K. *et al.* The Drought Response of Eastern US Oaks in the Context of Their Declining Abundance. *Bioscience* 72, 333-346 (2022).

29   Fargione, J. E. *et al.* Natural climate solutions for the United States. *Science Advances* 4, eaat1869 (2018).

30   Anderegg, W. R. L. *et al.* Future climate risks from stress, insects and fire across US forests. *Ecology Letters* 25, 1510-1520, doi:10.1111/ele.14018 (2022).

31   Malmsheimer, R. W. *et al.* Managing forests because carbon matters: integrating energy, products, and land management policy. *Journal of Forestry* 109, S7-S50 (2011).

32   Sanderman, J., Hengl, T. & Fiske, G. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences* 114, 9575-9580 (2017).

33   Eagle, A. J. & Olander, L. Greenhouse gas mitigation with agricultural land management activities in the United States—a side-by-side comparison of biophysical potential. *Advances in Agronomy* 115, 79-179 (2012).

34   Poeplau, C., Don, A., Ecosystems & Environment. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. *Agriculture, Ecosystems & Environment* 200, 33-41 (2015).

35   Paustian, K. *et al.* Agricultural soils as a sink to mitigate CO2 emissions. *Soil Use Management* 13, 230-244 (1997).

36   Paustian, K. *et al.* Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management* 10, 567-587 (2019).

37   McClelland, S. C., Paustian, K. & Schipanski, M. E. Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis. *Ecological Applications* 31, e02278 (2021).

38   Schlesinger, W. H. & Amundson, R. Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology* 25, 386-389 (2019).

39   Nahlik, A. M. & Fennessy, M. S. Carbon storage in US wetlands. *Nature Communications* 7, 1-9 (2016).

40   Griscom, B. W. *et al.* Natural climate solutions. *Proceedings of the National Academy of Sciences* 114, 11645-11650 (2017).

41   Drever, C. R. *et al.* Natural climate solutions for Canada. *Science Advances* 7, eabd6034 (2021).

42   Hemes, K. S., Chamberlain, S. D., Eichelmann, E., Knox, S. H. & Baldocchi, D. A biogeochemical compromise: The high methane cost of sequestering carbon in restored wetlands. *Geophysical Research Letters* 45, 6081-6091 (2018).

43   Taillardat, P., Thompson, B. S., Garneau, M., Trottier, K. & Friess, D. Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. *Interface Focus* 10, 20190129 (2020).

44   Hemes, K. S. *et al.* Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. 268, 202-214 (2019).

45   Zeng, N. & Hausmann, H. Wood Vault: remove atmospheric CO2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future. *Carbon Balance and Management* 17, 1-29 (2022).

46   Jackson, R. B. *et al.* Trading water for carbon with biological carbon sequestration. *Science* 310, 1944-1947 (2005).

47   Anderson, R. G. *et al.* Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment* 9, 174-182 (2011).

48   Betts, R. A. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408, 187-190 (2000).

49   Williams, C. A., Gu, H. & Jiao, T. Climate impacts of US forest loss span net warming to net cooling. *Science Advances* 7, eaax8859 (2021).

50   Bipartisan Policy Center (BPC). Federal Policies to Advance Natural Climate Solutions: Recommendations from the BPC Farm and Forest Carbon Solutiosn Task Force. (Washington, DC, USA, 2022). Available from https://bipartisanpolicy.org/report/federal-policies-to-advance-natural-climate-solutions/.

51   Joppa, L. *et al.* Microsoft's million-tonne CO2-removal purchase—lessons for net zero. *Nature* 597, 629-632 (2021).

52   Badgley, G. *et al.* Systematic over-crediting in California's forest carbon offsets program. *Global Change Biology* 28, 1433-1445 (2022).

53   Bossio, D. *et al.* The role of soil carbon in natural climate solutions. *Nature Sustainability* 3, 391-398 (2020).

54   Cook-Patton, S. C. *et al.* Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585, 545-550 (2020).

55   Oldfield, E. E. *et al.* Crediting agricultural soil carbon sequestration. *Science* 375, 1222-1225 (2022).

56   Anderson, C. M. *et al.* Natural climate solutions are not enough. *Science* 363, 933-934 (2019).

57   Baldocchi, D. & Penuelas, J. The physics and ecology of mining carbon dioxide from the atmosphere by ecosystems. *Global Change Biology* 25, 1191-1197 (2019).

58   Silva, L. C. *et al.* A generalizable framework for enhanced natural climate solutions. *Plant and Soil*, 1-22 (2022).

59   Wissner, N. S., Lambert. An Overview of Approaches - Ensuring safeguards and assessing sustainable development impacts in the voluntary carbon market. Foundation Development and Climate Alliance. Available from https://allianz-entwicklung-klima.de/wp-content/uploads/2022/03/220315_Studie_Allianz_Oeko-1.pdf. (2022)

60   Forest Trends' Ecosystem Marketplace. 'Markets in Motion': State of the Voluntary Carbon Markets 2021. Installment 1. . Forest Trends Association, Washington DC. Available from https://www.ecosystemmarketplace.com/publications/state-of-the-voluntary-carbon-markets-2021/. (2021).

61   Verra. *Verra Launches Pre-consultation on New Market Label*. Available from https://verra.org/verra-launches-pre-consultation-on-new-market-label/. (2022).

62   Anderson, C. M., Bicalho, T., Wallace, E., Letts, T., and Stevenson, M. Forest, land and agriculture Science Based Target setting guidance – draft for public consultation. Science Based Targets. Available from https://sciencebasedtargets.org/resources/files/FLAG-Guidance-Public-Consultation.pdf (2022).

63   Anderegg, W. R. *et al.* A climate risk analysis of Earth's forests in the 21st century. *Science* 377, 1099-1103 (2022).

64   Coffield, S. *et al.* Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. *Global Change Biology* (in press). (2022). https://doi.org/10.1111/gcb.16380.

65   Baldocchi, D. Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian Journal of Botany* 56, 1-26, (2008).

66   Novick, K. A. *et al.* The AmeriFlux network: A coalition of the willing. *Agricultural and Forest Meteorology* 249, 444-456 (2018).

67   Metzger, S. *et al.* From NEON field sites to data portal: a community resource for surface–atmosphere research comes online. *Bulletin of the American Meteorological Society* 100, 2305-2325 (2019).

68   Bechtold, W. A. & Patterson, P. L. *The enhanced forest inventory and analysis program--national sampling design and estimation procedures*. USDA Forest Service, Southern Research Station, 80 (2005).

69   Jung, M. *et al.* Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach. *Biogeosciences* 17, 1343-1365 (2020).

70   Domke, G. M., Oswalt, S. N., Walters, B. F. & Morin, R. S. Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the National Academy of Sciences* 117, 24649-24651 (2020).

71   Nave, L. E. *et al.* Reforestation can sequester two petagrams of carbon in US topsoils in a century. *Proceedings of the National Academy of Sciences* 115, 2776-2781 (2018).

72   VandenBygaart, A. J. A., Ecosystems & Environment. The myth that no-till can mitigate global climate change. *Agriculture, Ecosystems & Environment* 216, 98-99 (2016).

73   Amundson, R. & Biardeau, L. Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences* 115, 11652-11656 (2018).

74   Bradford, M. A. *et al.* Soil carbon science for policy and practice. *Nature Sustainability* 2, 1070-1072 (2019).

75   Paustian, K., Larson, E., Kent, J., Marx, E. & Swan, A. Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate* 8 (2019).

76   Post, W. M. & Kwon, K. C. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology* 6, 317-327 (2000).

77   Emde, D., Hannam, K. D., Most, I., Nelson, L. M. & Jones, M. D. Soil organic carbon in irrigated agricultural systems: A meta-analysis. *Global Change Biology* 27, 3898-3910 (2021).

78   Herzfeld, T., Heinke, J., Rolinski, S. & Müller, C. J. E. S. D. Soil organic carbon dynamics from agricultural management practices under climate change. 12, 1037-1055 (2021).

79   Stockmann, U. *et al.* The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture Ecosystems & Environment* 164, 80-99 (2013).

80   Spencer, S., Ogle, S.M., Breidt, F.J., Goebel, J.J. & Paustian, K. Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands. *Greenhouse Gas Measurement and Management* 1, 167-178 (2011).

81   Daryanto, S., Fu, B., Wang, L., Jacinthe, P.-A. & Zhao, W. Quantitative synthesis on the ecosystem services of cover crops. *Earth-Science Reviews* 185, 357-373 (2018).

82   Hanrahan, B. R. *et al.* Winter cover crops reduce nitrate loss in an agricultural watershed in the central US. *Agriculture, Ecosystems & Environment* 265, 513-523 (2018).

83   Kim, N., Zabaloy, M. C., Guan, K., Villamil, M. B. Do cover crops benefit soil microbiome? A meta-analysis of current research. *Soil Biology and Biochemistry* 142, 107701 (2020).

84   Powlson, D. S. *et al.* Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* 4, 678-683 (2014).

85   Ogle, S. M. *et al.* Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports* 9, 1-8 (2019).

86   Lugato, E., Leip, A. & Jones, A. Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. *Nature Climate Change* 8, 219-223 (2018).

87   Guenet, B. *et al.* Can N2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology* 27, 237-256 (2021).

88   Montes, F. *et al.* SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *Journal of Animal Science* 91, 5070-5094 (2013).

89   Ojima, D., Mosier, A., Del Grosso, S. & Parton, W. TRAGNET analysis and synthesis of trace gas fluxes. *Global Biogeochemical Cycles* 14, 995-997 (2000).

90   Jawson, M. *et al.* GRACEnet: Greenhouse gas reduction through agricultural carbon enhancement network. *Soil Tillage Research* 83, 167-172 (2005).

91   Del Grosso, S. *et al.* Introducing the GRACEnet/REAP data contribution, discovery, and retrieval system. *Journal of Environmental Quality* 42, 1274-1280 (2013).

92   Sanderman, J. & Baldock, J. A. Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective. *Environmental Research Letters* 5, 034003 (2010).

93   Aguilera, E., Lassaletta, L., Gattinger, A., Gimeno, B. S. ecosystems & environment. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment* 168, 25-36 (2013).

94   Uhran, B. *et al.* Wetland carbon in the United States: conditions and changes. *Wetland Carbon and Environmental Management* 21-31 (2021).

95   Mitsch, W. J. & Mander, Ü. Wetlands and carbon revisited. *Ecological Engineering* 114, 1-6 (2018).

96   Malone, S. L. *et al.* Gaps in network infrastructure limit our understanding of biogenic methane emissions for the United States. *Biogeosciences* 19, 2507-2522 (2022).

97   Minick, K. J. *et al.* Wetland microtopography alters response of potential net CO2 and CH4 production to temperature and moisture: Evidence from a laboratory experiment. *Geoderma* 402, 115367 (2021).

98   Diamond, J. S. *et al.* A little relief: Ecological functions and autogenesis of wetland microtopography. *Wiley Interdisciplinary Reviews: Water* 8, e1493 (2021).

99   Mack, S. K. *et al.* A blue carbon pilot project: Lessons learned. *Carbon Management* 13, 420-434 (2022).

100   Morin, T. *et al.* Combining eddy-covariance and chamber measurements to determine the methane budget from a small, heterogeneous urban floodplain wetland park. *Agricultural and Forest Meteorology* 237, 160-170 (2017).

101   Rey-Sanchez, A., Morin, T., Stefanik, K., Wrighton, K. & Bohrer, G. Determining total emissions and environmental drivers of methane flux in a Lake Erie estuarine marsh. *Ecological Engineering* 114, 7-15 (2018).

102   Moomaw, W. R. *et al.* Wetlands in a changing climate: science, policy and management. *Wetlands* 38, 183-205 (2018).

103   Were, D. *et al.* Carbon sequestration by wetlands: a critical review of enhancement measures for climate change mitigation. *Earth Systems & Environment* 3, 327-340 (2019).

104   Lu, M. *et al.* Anthropogenic disturbances caused declines in the wetland area and carbon pool in China during the last four decades. *Global Change Biology* 27, 3837-3845 (2021).

105   Abril, G. & Borges, A. V. Ideas and perspectives: carbon leaks from flooded land: do we need to replumb the inland water active pipe? *Biogeosciences* 16, 769-784 (2019).

106   Bogard, M. J. *et al.* Hydrologic export is a major component of coastal wetland carbon budgets. *Global Biogeochemical Cycles* 34, e2019GB006430 (2020).

107   Arias-Ortiz, A. *et al.* Tidal and nontidal marsh restoration: A trade-off between carbon sequestration, methane emissions, and soil accretion. *Journal of Geophysical Research-Biogeosciences* 126, e2021JG006573 (2021).

108   Hurtt, G. *et al.* Beyond MRV: high-resolution forest carbon modeling for climate mitigation planning over Maryland, USA. *Environmental Research Letters* 14, 045013 (2019).

109   Law, B. E. *et al.* Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences* 115, 3663-3668 (2018).

110   Ma, L. *et al.* High-resolution forest carbon modelling for climate mitigation planning over the RGGI region, USA. *Environmental Research Letters* 16, 045014 (2021).

111   Domke, G. *et al.* Toward inventory-based estimates of soil organic carbon in forests of the United States. *Ecological Applications* 27, 1223-1235 (2017).

112   Giebink, C. L. *et al.* The policy and ecology of forest-based climate mitigation: challenges, needs, and opportunities. *Plant and Soil*, 1-28 (2022).

113   Hemes, K. S. *et al.* An ecosystem-scale flux measurement strategy to assess natural climate solutions. *Environmental Science and Technology* 55, 3494-3504 (2021).

114   Slessarev, E., Zelikova, J., Hamman, J., Cullenward, D. & Freeman, J. Depth matters for soil carbon accounting. CarbonPlan, available from https://carbonplan.org/research/soil-depth-sampling. (2021).

115   Du, Z. *et al.* The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis. *Agriculture, Ecosystems & Environment* 236, 1-11 (2017).

116   Cai, A. *et al.* Declines in soil carbon storage under no tillage can be alleviated in the long run. *Geoderma* 425, 116028 (2022).

117   Kravchenko, A. & Robertson, G. Whole-profile soil carbon stocks: The danger of assuming too much from analyses of too little. *Soil Science Society of America Journal* 75, 235-240 (2011).

118   Meurer, K. H., Haddaway, N. R., Bolinder, M. A. & Kätterer, T. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews* 177, 613-622 (2018).

119   Ogle, S. M. *et al.* Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports* 9, 1-8 (2019).

120   McCarthy, H. R. *et al.* Re-assessment of plant carbon dynamics at the Duke free-air CO2 enrichment site: interactions of atmospheric [CO2] with nitrogen and water availability over stand development. *New Phytologist* 185, 514-528 (2010).

121   Trugman, A. T. *et al.* Climate and plant trait strategies determine tree carbon allocation to leaves and mediate future forest productivity. 25, 3395-3405 (2019).

122   Nave, L. E. *et al.* The role of reforestation in carbon sequestration. *New Forests* 50, 115-137 (2019).

123   Woodall, C.W. *et al.* Decadal dead wood biomass dynamics of coterminous US forests. *Environmental Research Letters* 16, p.104034 (2021).

124   Cabon, A. *et al.* Cross-biome synthesis of source versus sink limits to tree growth. *Science* 376, 758-761 (2022).

125   Green, J. K. & Keenan, T. F. The limits of forest carbon sequestration. *Science* 376, 692-693 (2022).

126   Kannenberg, S. A. *et al.* Drought-induced decoupling between carbon uptake and tree growth impacts forest carbon turnover time. *Agricultural and Forest Meteorology* 322, 108996 (2022).

127   Sun, W. *et al.* Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Global Change Biology* 26, 3325-3335 (2020).

128   Ogle, S. M., Swan, A., Paustian, K. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture Ecosystems & Environment* 149, 37-49 (2012).

129   Dubayah, R. *et al.* GEDI launches a new era of biomass inference from space. *Environmental Research Letters* 17, doi:10.1088/1748-9326/ac8694 (2022).

130   Zhou, Y., Williams, C. A., Hasler, N., Gu, H. & Kennedy, R. Beyond biomass to carbon fluxes: application and evaluation of a comprehensive forest carbon monitoring system. *Environmental Research Letters* 16, 055026 (2021).

131   Williams, C. A., Gu, H. & Jiao, T. Climate impacts of US forest loss span net warming to net cooling. *Science Advances* 7, doi:10.1126/sciadv.aax8859 (2021).

132   Ellison, D. *et al.* Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* 43, 51-61 (2017).

133   Wong, S., Cowan, I. & Farquhar, G. J. N. Stomatal conductance correlates with photosynthetic capacity. *Nature* 282, 424-426 (1979).

134   Yin, Y. *et al.* Cropland carbon uptake delayed and reduced by 2019 Midwest floods. *AGU Advances* 1, e2019AV000140 (2020).

135   Windisch, M. G., Davin, E. L. & Seneviratne, S. I. Prioritizing forestation based on biogeochemical and local biogeophysical impacts. *Nature Climate Change* 11, 867-871 (2021).

136   Bagley, J. E., Miller, J., Bernacchi, C. J. Biophysical impacts of climate-smart agriculture in the Midwest United States. *Plant Cell and Environment* 38, 1913-1930 (2015).

137   Anderson, R. G. *et al.* Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment* 9, 174-182, doi:10.1890/090179 (2011).

138   Juang, J. Y., Katul, G., Siqueira, M., Stoy, P. & Novick, K. Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. *Geophysical Research Letters* 34, doi:10.1029/2007gl031296 (2007).

139   Zhang, Q. *et al.* Reforestation and surface cooling in temperate zones: Mechanisms and implications. *Global Change Biology* 26, 3384-3401, doi:10.1111/gcb.15069 (2020).

140   Baldocchi, D. & Ma, S. How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA. *Tellus B: Chemical & Physical Meteorology* 65, 19994 (2013).

141   Lee, X. *et al.* Observed increase in local cooling effect of deforestation at higher latitudes. *Nature* 479, 384-387, doi:10.1038/nature10588 (2011).

142   Luyssaert, S. *et al.* Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change* 4, 389-393 (2014).

143   Bright, R. M. *et al.* Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change* 7, 296-302 (2017).

144   Cerasoli, S., Yin, J. & Porporato, A. Cloud cooling effects of afforestation and reforestation at midlatitudes. *Proceedings of the National Academy of Sciences* 118, e2026241118 (2021).

145   Hemes, K. S. *et al.* A unique combination of aerodynamic and surface properties contribute to surface cooling in restored wetlands of the Sacramento-San Joaquin Delta, California. *Journal of Geophysical Research-Biogeosciences* 123, 2072-2090 (2018).

146   Liu, W. *et al.* Biophysical effects of paddy rice expansion on land surface temperature in Northeastern Asia. *Agricultural and Forest Meteorology* 315, 108820 (2022).

147   Duman, T., Huang, C.-W., Litvak, M. E. Recent land cover changes in the Southwestern US lead to an increase in surface temperature. *Agricultural and Forest Meteorology* 297, 108246 (2021).

148   Schwingshackl, C., Hirschi, M. & Seneviratne, S. I. Global Contributions of Incoming Radiation and Land Surface Conditions to Maximum Near-Surface Air Temperature Variability and Trend. *Geophysical Research Letters* 45, 5034-5044, doi:10.1029/2018gl077794 (2018).

149   Novick, K. A. & Katul, G. G. The Duality of Reforestation Impacts on Surface and Air Temperature. *Journal of Geophysical Research-Biogeosciences* 125, doi:10.1029/2019jg005543 (2020).

150   Teuling, A. & Seneviratne, S. I. Contrasting spectral changes limit albedo impact on land-atmosphere coupling during the 2003 European heat wave. *Geophysical Research Letters* 35 (2008).

151   Sungmin, O. *et al.* The role of climate and vegetation in regulating drought-heat extremes. *Journal of Climate* 1, 1-21 (2022).

152   Winckler, J., Lejeune, Q., Reick, C. H. & Pongratz, J. Nonlocal effects dominate the global mean surface temperature response to the biogeophysical effects of deforestation. *Geophysical Research Letters* 46, 745-755 (2019).

153   Winckler, J., Reick, C. H. & Pongratz, J. Robust identification of local biogeophysical effects of land-cover change in a global climate model. *Journal of Climate* 30, 1159-1176 (2017).

154   Pongratz, J. *et al.* Land use effects on climate: current state, recent Progress, and emerging topics. *Current Climate Change Reports*, 1-22 (2021).

155   Swann, A. L. *et al.* Continental-scale consequences of tree die-offs in North America: identifying where forest loss matters most. *Environmental Research Letters* 13, 055014 (2018).

156   Anderegg, W. R. *et al.* Climate-driven risks to the climate mitigation potential of forests. *Science* 368, eaaz7005 (2020).

157   Badgley, G. *et al.* California's forest carbon offsets buffer pool is severely undercapitalized. *Frontiers in Forests and Global Change* 5, 930426. (2022).

158   Archer, D. *et al.* Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth Planetary Sciences* 37 (2009).

159   Pierrehumbert, R. T. Short-lived climate pollution. *Annual Review of Earth Planetary Sciences* 42, 341-379 (2014).

160   Kirschbaum, M. U. Temporary carbon sequestration cannot prevent climate change. *Mitigation and Adaptation Strategies for Global Change* 11, 1151-1164 (2006).

161   Leifeld, J. & Keel, S. G. Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks. *Geoderma* 423, 115971 (2022).

162   Sierra, C. A., Crow, S. E., Heimann, M., Metzler, H. & Schulze, E.-D.. The climate benefit of carbon sequestration. *Biogeosciences* 18, 1029-1048 (2021).

163   Seidl, R. *et al.* Forest disturbances under climate change. *Nature Climate Change* 7, 395-402 (2017).

164   Barbero, R., Abatzoglou, J. T., Larkin, N. K., Kolden, C. A. & Stocks, B. Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire* 24, 892-899 (2015).

165   Moritz, M. A. *et al.* Climate change and disruptions to global fire activity. *Ecosphere* 3, 1-22 (2012).

166   Hurteau, M. D., North, M. P., Koch, G. W. & Hungate, B. A. Managing for disturbance stabilizes forest carbon. *Proceedings of the National Academy of Sciences* 116, 10193-10195 (2019).

167   Williams, A. P. & Abatzoglou, J. T. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. *Current Climate Change Reports* 2, 1-14 (2016).

168   Allen, C. D., Breshears, D. D. & McDowell, N. G. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* 6, 1-55 (2015).

169   Campbell, J. L., Harmon, M. E., Mitchell, S. R. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? *Frontiers in Ecology and the Environment* 10, 83-90 (2012).

170   Buchholz, T. *et al.* Probability-based accounting for carbon in forests to consider wildfire and other stochastic events: synchronizing science, policy, and carbon offsets. *Mitigation and Adaptation Strategies for Global Change* 27, 1-21 (2022).

171   Krofcheck, D., Remy, C. C., Keyser, A. & Hurteau, M. Optimizing forest management stabilizes carbon under projected climate and wildfires. *Journal of Geophysical Research-Biogeosciences* 124, 3075-3087 (2019).

172   Liang, S., Hurteau, M. D., Westerling, A. L. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. *Frontiers in Ecology and the Environment* 16, 207-212 (2018).

173   Lavallee, J. M., Soong, J. L. & Cotrufo, M. F. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology* 26, 261-273 (2020).

174   Rocci, K. S., Lavallee, J. M., Stewart, C. E. & Cotrufo, M. F. Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and particulate organic matter: A meta-analysis. *Science of The Total Environment* 793, 148569 (2021).

175   Kleber, M. *et al.* Mineral–organic associations: formation, properties, and relevance in soil environments. *Advances in Agronomy* 130, 1-140 (2015).

176   Georgiou, K. *et al.* Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications* 13, 1-12 (2022).

177   Spokas, K. A. Review of the stability of biochar in soils: predictability of O: C molar ratios. *Carbon Management* 1, 289-303 (2010).

178   Ippolito, J. A. *et al.* Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar* 2, 421-438 (2020).

179   Nelson, D. R., Bledsoe, B. P., Ferreira, S. & Nibbelink, N. P. Challenges to realizing the potential of nature-based solutions. *Current Opinion in Environmental Sustainability* 45, 49-55 (2020).

180   Yoder, L., Ward, A. S., Dalrymple, K., Spak, S. & Lave, R. An analysis of conservation practice adoption studies in agricultural human-natural systems. *Journal of Environmental Management* 236, 490-498 (2019).

181   De Kauwe, M. G., Medlyn, B. E. & Tissue, D. T. To what extent can rising [CO2] ameliorate plant drought stress? *New Phytologist* 231, 2118-2124 (2021).

182   Sanderson, B. M. & Fisher, R. A. A fiery wake-up call for climate science. *Nature Climate Change* 10, 175-177 (2020).

183   Trugman, A. T. Integrating plant physiology and community ecology across scales through trait-based models to predict drought mortality. *New Phytologist* 234, 21-27 (2022).

184   Williams, M. *et al.* Improving land surface models with FLUXNET data. *Biogeosciences* 6, 1341-1359 (2009).

185   Xiao, J., Chen, J., Davis, K. J. & Reichstein, M. Advances in upscaling of eddy covariance measurements of carbon and water fluxes. *Journal of Geophysical Research-Biogeosciences* 117 (2012).

186   Oliver, R. J. *et al.* Improved representation of plant physiology in the JULES-vn5. 6 land surface model: photosynthesis, stomatal conductance and thermal acclimation. *Geoscientific Model Development* 15, 5567-5592 (2022).

187   Zhou, W. *et al.* Quantifying carbon budget, crop yields and their responses to environmental variability using the ecosys model for US Midwestern agroecosystems. *Agricultural and Forest Meteorology* 307, 108521 (2021).

188   Keenan, T. F., Davidson, E., Moffat, A. M., Munger, W. & Richardson, A. D. Using model-data fusion to interpret past trends, and quantify uncertainties in future projections, of terrestrial ecosystem carbon cycling. *Global Change Biology* 18, 2555-2569 (2012).

189   Lawrence, D. M. *et al.* The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems* 11, 4245-4287 (2019).

190   Lombardozzi, D. L. *et al.* Simulating agriculture in the Community Land Model version 5. *Journal of Geophysical Research-Biogeosciences* 125, e2019JG005529 (2020).

191   Pongratz, J. *et al.* Models meet data: Challenges and opportunities in implementing land management in Earth system models. *Global Change Biology* 24, 1470-1487 (2018).

192   Sulman, B. N., Phillips, R. P., Oishi, A. C., Shevliakova, E. & Pacala, S. W. Microbe-driven turnover offsets mineral-mediated storage of soil carbon under elevated CO2. *Nature Climate Change* 4, 1099-1102 (2014).

193   Abramoff, R. Z. *et al.* Improved global-scale predictions of soil carbon stocks with Millennial Version 2. *Soil Biology and Biochemistry* 164, 108466 (2022).

194   Fisher, R. A. *et al.* Vegetation demographics in Earth System Models: A review of progress and priorities. *Global Change Biology* 24, 35-54 (2018).

195   Giltrap, D. L., Li, C., Saggar, S. DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. *Agriculture, Ecosystems & Environment* 136, 292-300 (2010).

196   Parton, W. J., Hartman, M., Ojima, D., Schimel, D. DAYCENT and its land surface submodel: description and testing. *Global Planetary Change* 19, 35-48 (1998).

197   Berardi, D. *et al.* 21st-century biogeochemical modeling: challenges for Century-based models and where do we go from here? *Bioenergy* 12, 774-788 (2020).

198   Paustian, K. *et al.* Field-and farm-scale assessment of soil greenhouse gas mitigation using COMET-Farm. *Precision Conservation: geospatial techniques for agricultural and natural resources conservation* 59, 341-359 (2017).

199   Zhang, Y. *et al.* DayCent model predictions of NPP and grain yields for agricultural lands in the contiguous US. *Journal of Geophysical Research-Biogeosciences* 125, e2020JG005750 (2020).

200   Dietze, M. C., Lebauer, D. S., Kooper, R. On improving the communication between models and data. *Plant Cell and Environment* 36, 1575-1585 (2013).

201   Kyker-Snowman, E. *et al.* Increasing the spatial and temporal impact of ecological research: A roadmap for integrating a novel terrestrial process into an Earth system model. *Global Change Biology* 28, 665-684 (2022).

202   Moore, D.J.P. A framework for incorporating ecology into Earth System Models is urgently needed. *Global Change Biology* 28, 343-345 (2022).

203   Broekhoff, D., Gillenwater, M., Colbert-Sangree, T. & Cage, P. Securing climate benefit: a guide to using carbon offsets. *Stockholm Environment Institute & Greenhouse Gas Management Institute* 60 (2019).

204   Gifford, R. M. & Roderick, M. L. Soil carbon stocks and bulk density: spatial or cumulative mass coordinates as a basis of expression? *Global Change Biology* 9, 1507-1514 (2003).

205   Wendt, J. & Hauser, S. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science* 64, 58-65 (2013).

206   von Haden, A. C., Yang, W. H. & DeLucia, E. H. Soils' dirty little secret: Depth-based comparisons can be inadequate for quantifying changes in soil organic carbon and other mineral soil properties. *Global Change Biology* 26, 3759-3770 (2020).

207   Verra, https://verra.org/methodologies

208   Climate Action Reserve Protocols. https://www.climateactionreserve.org/how/protocols/

209   California Air Resources Board (CARB). https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/protocols/usforest/forestprotocol2015.pdf.

210   RGGI – The Regional Greenhouse Gas Initiative. https://www.rggi.org/allowance-tracking/offsets/offset-categories/forestry-afforestation

211   Wise, L. *et al.* Optimizing sequestered carbon in forest offset programs: balancing accounting stringency and participation. *Carbon Balance and Management* 14, 1-11 (2019).

212   Pan, C. *et al.* Key challenges and approaches to addressing barriers in forest carbon offset projects. *Journal of Forestry Research*, 1-14 (2022).

213   Rejesus, R. M. *et al.* Economic dimensions of soil health practices that sequester carbon: Promising research directions. *Journal of Soil and Water Conservation* 76, 55A-60A (2021).

214   California Department of Food and Agriculture (CDFA). Healthy Soils Program. https://www.cdfa.ca.gov/oefi/healthysoils/.

215   Charmakar, S., Oli, B. N., Joshi, N. R., Maraseni, T. N. & Atreya, K. Forest carbon storage and species richness in FSC certified and non-certified community forests in Nepal. *Small-scale Forestry* 20, 199-219 (2021).

216   USDA. Partnerships for Climate-Smart Commodities. https://www.usda.gov/climate-solutions/climate-smart-commodities.

217   Science Based Targets Initiative. https://sciencebasedtargets.org/

218   Family Forest Foundation. Determining a True Carbon Benefit Part II: Baselines. https://www.forestfoundation.org/why-we-do-it/family-forest-blog/determining-a-true-carbon-benefit-part-2-baselines/

219   Oldfield, E. *et al.* Agricultural soil carbon credits: Making sense of protocols for carbon sequestration and net greenhouse gas removals. (2021). Environmental Defense Fund. Available from file:///C:/Users/knovick/Downloads/oldfield%20soc%20mrv%20presentation-nasem.pdf.

220   Crookston, N. L., Dixon, G. E. The forest vegetation simulator: a review of its structure, content, and applications. *Computers and Electronics in Agriculture* 49, 60-80 (2005).

221   Schneider, L. Assessing the additionality of CDM projects: practical experiences and lessons learned. *Climate Policy* 9, 242-254 (2009).

222   Cames, M. *et al.* How additional is the clean development mechanism. 2017-2004 (Oko-Institut, 2016). Available from https://climate.ec.europa.eu/system/files/2017-04/clean_dev_mechanism_en.pdf.

223   Erickson, P., Lazarus, M. & Spalding-Fecher, R. Net climate change mitigation of the Clean Development Mechanism. *Energy Policy* 72, 146-154 (2014).

224   Schneider, L. & Kollmuss, A. Perverse effects of carbon markets on HFC-23 and SF6 abatement projects in Russia. *Nature Climate Change* 5, 1061-1063 (2015).

225   Wara, M. Is the global carbon market working? *Nature* 445, 595-596 (2007).

226   Haya, B. *et al.* Managing uncertainty in carbon offsets: insights from California's standardized approach. *Climate Policy* 20, 1112-1126 (2020).

227   Bento, A., Kanbur, R. & Leard, B. On the importance of baseline setting in carbon offsets markets. *Climatic Change* 137, 625-637 (2016).

228   Liu, X. & Cui, Q. Baseline manipulation in voluntary carbon offset programs. *Energy Policy* 111, 9-17 (2017).

229   Fischer, C.. Project-based mechanisms for emissions reductions: balancing trade-offs with baselines. *Energy Policy* 33, 1807-1823 (2005).

230   Millard-Ball, A. & Management. The trouble with voluntary emissions trading: Uncertainty and adverse selection in sectoral crediting programs. *Journal of Environmental Economics & Management* 65, 40-55 (2013).

231   Montero, J.-P. Voluntary compliance with market-based environmental policy: Evidence from the US Acid Rain Program. *Journal of Political Economy* 107, 998-1033 (1999).

232   Anderson-Teixeira, K. J. & Belair, E. P. Effective forest-based climate change mitigation requires our best science. *Global Change Biology* 28, 1200-1203 (2022).

233   Haim, D., White, E. M., Alig, R. Agriculture afforestation for carbon sequestration under carbon markets in the United States: Leakage behavior from regional allowance programs. *Applied Economic Perspectives and Policy* 38, 132-151 (2016).

234   de Gruijter, J. J. *et al.* Farm-scale soil carbon auditing. *Pedometrics*, 693-720 (2018).

235   Brus, D. J. G. Sampling for digital soil mapping: A tutorial supported by R scripts. *Geoderma* 338, 464-480 (2019).

236   Young, M. A. *et al.* Optimal soil carbon sampling designs to achieve cost-effectiveness: a case study in blue carbon ecosystems. *Biology Letters* 14, 20180416 (2018).

237   Jiang, C. & Ryu, Y. Multi-scale evaluation of global gross primary productivity and evapotranspiration products derived from Breathing Earth System Simulator (BESS). *Remote Sensing of Environment* 186, 528-547 (2016).

238   Abramowitz, G., Leuning, R., Clark, M. & Pitman, A. Evaluating the performance of land surface models. *Journal of Climate* 21, 5468-5481 (2008).

239   Villarreal, S. & Vargas, R. Representativeness of FLUXNET sites across Latin America. *Journal of Geophysical Research-Biogeosciences* 126, e2020JG006090 (2021).

240   Chu, H., Baldocchi, D. D., John, R., Wolf, S. & Reichstein, M. Fluxes all of the time? A primer on the temporal representativeness of FLUXNET. *Journal of Geophysical Research-Biogeosciences* 122, 289-307 (2017).

241   Domke, G. M. *et al.* Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2018. USDA Forest Servce – Northern Research Station. Resource Update FS-227. Madison, WI. (2020).

242   Trugman, A. T., Anderegg, L. D., Shaw, J. D. & Anderegg, W. R. Trait velocities reveal that mortality has driven widespread coordinated shifts in forest hydraulic trait composition. *Proceedings of the National Academy of Sciences* 117, 8532-8538 (2020).

243   Rossel, R. V., Adamchuk, V., Sudduth, K., McKenzie, N. & Lobsey, C. Proximal soil sensing: An effective approach for soil measurements in space and time. *Advances in Agronomy* 113, 243-291 (2011).

244   Sanderman, J. *et al.* Can Agricultural Management Induced Changes in Soil Organic Carbon Be Detected Using Mid-Infrared Spectroscopy? *Remote Sensing* 13, 2265 (2021).

245   Pei, X., Sudduth, K. A., Veum, K. S. & Li, M. Improving in-situ estimation of soil profile properties using a multi-sensor probe. *Sensors* 19, 1011 (2019).

246 Li, S., Viscarra Rossel, R. A. & Webster, R.. The cost-effectiveness of reflectance spectroscopy for estimating soil organic carbon. *European Journal of Soil Science* 73, e13202 (2022).

247 Hutengs, C., Seidel, M., Oertel, F., Ludwig, B. & Vohland, M. In situ and laboratory soil spectroscopy with portable visible-to-near-infrared and mid-infrared instruments for the assessment of organic carbon in soils. *Geoderma* 355, 113900 (2019).

248 Angelopoulou, T., Tziolas, N., Balafoutis, A., Zalidis, G. & Bochtis, D. Remote sensing techniques for soil organic carbon estimation: A review. *Remote Sensing* 11, 676 (2019).

249 Shepherd, K. D. *et al.* A global soil spectral calibration library and estimation service. *Soil Security* 7, 100061 (2022).

250 Babst, F. *et al.* A tree-ring perspective on the terrestrial carbon cycle. *Oecologia* 176, 307-322 (2014).

251 Babst, F. *et al.* When tree rings go global: Challenges and opportunities for retro-and prospective insight. *Quaternary Science Reviews* 197, 1-20 (2018).

252 Evans, M. E. *et al.* Fusing tree-ring and forest inventory data to infer influences on tree growth. *Ecosphere* 8, e01889 (2017).

253 Evans, M. E. *et al.* Adding tree rings to North America's national forest inventories: An essential tool to guide drawdown of atmospheric CO2. *BioScience* 72, 233-246 (2022).

254 Heilman, K. A. *et al.* Ecological forecasting of tree growth: Regional fusion of tree-ring and forest inventory data to quantify drivers and characterize uncertainty. *Global Change Biology* 28, 2442-2460, doi:10.1111/gcb.16038 (2022).

255 Sullivan, P. F. & Csank, A. Z. Contrasting sampling designs among archived datasets: implications for synthesis efforts. *Tree Physiology* 36, 1057-1059 (2016).

256 Klesse, S. *et al.* Sampling bias overestimates climate change impacts on forest growth in the southwestern United States. *Nature Communications* 9, 1-9 (2018).

257 Anderson-Teixeira, K. J. *et al.* CTFS-Forest GEO: a worldwide network monitoring forests in an era of global change. *Global Change Biology* 21, 528-549 (2015).

258 Crisp, D. *et al.* The orbiting carbon observatory (OCO) mission. In *Trace Constituents in the Troposphere and Lower Stratosphere* Vol. 34 *Advances in Space Research-Series* (eds J. P. Burrows & A. M. Thompson) 700-709 (2004).

259 Sun, Y. *et al.* Overview of Solar-Induced chlorophyll Fluorescence (SIF) from the Orbiting Carbon Observatory-2: Retrieval, cross-mission comparison, and global monitoring for GPP. *Remote Sensing of Environment* 209, 808-823 (2018).

260 Butz, A. *et al.* Toward accurate CO2 and CH4 observations from GOSAT. *Geophysical Research Letters* 38 (2011).

261 Duren, R. *et al.* Carbon Mapper: on-orbit performance predictions and airborne prototyping. In *AGU Fall Meeting Abstracts.* A53F-05 (2021).

262 Wolfe, G. M. *et al.* The NASA carbon airborne flux experiment (CARAFE): instrumentation and methodology. *Atmospheric Measurement Techniques* 11, 1757-1776 (2018).

263 Ordway, E. M. *et al.* Leveraging the NEON Airborne Observation Platform for socio-environmental systems research. *Ecosphere* 12, e03640 (2021).

264 Lamb, R. L. *et al.* Context and future directions for integrating forest carbon into sub-national climate mitigation planning in the RGGI region of the US. *Environmental Research Letters* 16, 063001 (2021).

265 Babcock, C. *et al.* Geostatistical estimation of forest biomass in interior Alaska combining Landsat-derived tree cover, sampled airborne lidar and field observations. *Remote Sensing of Environment* 212, 212-230 (2018).

266 Simard, M. *et al.* Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. *Nature Geoscience* 12, 40-45 (2019).

267 Drusch, M. *et al.* The fluorescence explorer mission concept—ESA's earth explorer 8. *IEEE Transactions on Geoscience Remote Sensing* 55, 1273-1284 (2016).

268 Cawse-Nicholson, K. *et al.* NASA's surface biology and geology designated observable: A perspective on surface imaging algorithms. *Remote Sensing of Environment* 257, 112349 (2021).

269 Pignatti, S. *et al.* The PRISMA hyperspectral mission: Science activities and opportunities for agriculture and land monitoring. In *2013 IEEE International Geoscience and Remote Sensing Symposium-IGARSS.* 4558-4561 (IEEE).

270 Nieke, J. & Rast, M. Towards the copernicus hyperspectral imaging mission for the environment (CHIME). In *Igarss 2018-2018 IEEE International Geoscience and Remote Sensing Symposium.* 157-159 (2018).

271 Guanter, L. *et al.* The EnMAP spaceborne imaging spectroscopy mission for earth observation. *Remote Sensing* 7, 8830-8857 (2015).

272 Krutz, D. *et al.* The instrument design of the DLR earth sensing imaging spectrometer (DESIS). *Sensors* 19, 1622 (2019).

273 Barnes, M. L., Yoder, L. & Khodaee, M. Detecting winter cover crops and crop residues in the midwest US using machine learning classification of thermal and optical imagery. *Remote Sensing* 13, 1998 (2021).

274   Seifert, C. A., Azzari, G. & Lobell, D. B. Satellite detection of cover crops and their effects on crop yield in the Midwestern United States. *Environmental Research Letters* 13, 064033 (2018).

275   Fisher, J. B. *et al.* ECOSTRESS: NASA's Next Generation Mission to Measure Evapotranspiration From the International Space Station. *Water Resources Research* 56 (2020).

276   Tinkham, W. T. *et al.* Applications of the United States Forest Inventory and Analysis dataset: A review and future directions. *Canadian Journal of Forest Research* 48, 1251-1268 (2018).

277   Barnes, M. L. *et al.* Improved dryland carbon flux predictions with explicit consideration of water-carbon coupling. *Communications Earth & Environment* 2, doi:10.1038/s43247-021-00308-2 (2021).

278   Jung, M. *et al.* The FLUXCOM ensemble of global land-atmosphere energy fluxes. *Scientific Data* 6, 1-14 (2019).

279   Reichstein, M. *et al.* Deep learning and process understanding for data-driven Earth system science. *Nature* 566, 195-204 (2019).

280   Heilman, K. A. *et al.* Ecological forecasting of tree growth: Regional fusion of tree-ring and forest inventory data to quantify drivers and characterize uncertainty. *Global Change Biology* 28, 2442-2460 (2022).

281   Arora, V. K. *et al.* Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences* 17, 4173-4222 (2020).

282   Friedlingstein, P. *et al.* Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate* 27, 511-526 (2014).

283   Bonan, G. B. & Doney, S. C. Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. *Science* 359, eaam8328 (2018).

284   Keller, M., Schimel, D. S., Hargrove, W. W. & Hoffman, F. A continental strategy for the National Ecological Observatory Network. *Frontiers in Ecology and the Environment* 6, 282-284 (2008).

285   Hobbie, J. E., Carpenter, S. R., Grimm, N. B., Gosz, J. R. & Seastedt, T. R. The US Long Term Ecological Research Program. *Bioscience* 53, 21-32 (2003).

286   Kleinman, P. J. A. *et al.* Advancing the Sustainability of US Agriculture through Long-Term Research. *Journal of Environmental Quality* 47, 1412-1425 (2018).

287   Pastorello, G. *et al.* The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. *Scientific Data* 7, 1-27 (2020).

288   *Environmental Data Initiative*. https://edirepository.org/about/about-edi.

289   DataOne. https://www.dataone.org/.

290   NSF. *Center for Advancement and Synthesis of Open Environmental Data and Sciences*, https://beta.nsf.gov/funding/opportunities/center-advancement-and-synthesis-open-environmental-data-and-sciences.

291   Wilm, H. Statistical control of hydrologic data from experimental watersheds. *EOS Transactions, American Geophysial Union* 24, 618-624 (1943).

292   Hornbeck, J., Martin, C. & Eagar, C. Summary of water yield experiments at Hubbard Brook experimental forest, New Hampshire. *Canadian Journal of Forest Research* 27, 2043-2052 (1997).

293   Knapp, A. K. *et al.* Past, present, and future roles of long-term experiments in the LTER network. *BioScience* 62, 377-389 (2012).

294   Borer, E. T. *et al.* A decade of insights into grassland ecosystem responses to global environmental change. *Nature Ecology and Evolution* 1, 1-7 (2017).

295   Smith, M. D. *et al.* Drought-Net: A global network merging observations, experiments, and modeling to forecast terrestrial ecosystem sensitivity to drought. In *AGU Fall Meeting Abstracts.* B11J-06. (2016).

296   Yahdjian, L. *et al.* Why coordinated distributed experiments should go global. *BioScience* 71, 918-927 (2021).

297   Fraser, L. H. *et al.* Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment* 11, 147-155 (2013).

298   RESTOR.ECO. https://restor.eco.

299   Weintraub, S. R. *et al.* Leveraging environmental research and observation networks to advance soil carbon science. *Journal of Geophysical Research-Biogeosciences* 124, 1047-1055 (2019).

300   Malhotra, A. *et al.* The landscape of soil carbon data: emerging questions, synergies and databases. *Progress in Physical Geography: Earth & Environment* 43, 707-719 (2019).

301   Joiner, J. *et al.* Estimation of terrestrial global gross primary production (GPP) with satellite data-driven models and eddy covariance flux data. *Remote Sensing* 10, 1346 (2018).

302   Dechant, B. *et al.* NIRVP: A robust structural proxy for sun-induced chlorophyll fluorescence and photosynthesis across scales. *Remote Sensing of Environment* 268, 112763 (2022).

303   Konings, A. G. *et al.* Detecting forest response to droughts with global observations of vegetation water content. *Global Change Biology* 27, 6005-6024, doi:10.1111/gcb.15872 (2021).

304   Schimel, D. *et al.* Flux towers in the sky: global ecology from space. *New Phytologist* 224, 570-584, doi:10.1111/nph.15934 (2019).

305   Dietze, M. C. *et al.* Iterative near-term ecological forecasting: Needs, opportunities, and challenges. *Proceedings of the National Academy of Sciences* 115, 1424-1432 (2018).

306   De Hertog, S. J. *et al.* The biogeophysical effects of idealized land cover and land management changes in Earth System Models. *Earth System Dynamics* 13, 1305-1350 (2022).

307   Delwiche, K. B. *et al.* FLUXNET-CH 4: a global, multi-ecosystem dataset and analysis of methane seasonality from freshwater wetlands. *Earth System Science Data* 13, 3607-3689 (2021).

308   Griffis, T. *et al.* Reconciling the differences between top-down and bottom-up estimates of nitrous oxide emissions for the US Corn Belt. *Global Biogeochemical Cycles* 27, 746-754 (2013).

309   Tebaldi, C. *et al.* Climate model projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6. *Earth System Dynamics* 12, 253-293 (2021).

310   Huntzinger, D. *et al.* The north american carbon program multi-scale synthesis and terrestrial model intercomparison project–part 1: Overview and experimental design. *Geoscientific Model Development* 6, 2121-2133 (2013).

311   Wiesner, S., Desai, A. R., Duff, A. J., Metzger, S. & Stoy, P. C. Quantifying the natural climate solution potential of agricultural systems by combining eddy covariance and remote sensing. *Journal of Geophysical Research: Biogeosciences*, e2022JG006895 (2022).

312   NASA. *Carbon Monitoring System*. https://carbon.nasa.gov

313   USDA. *Climate Hubs*. https://www.climatehubs.usda.gov

314   State of Colorado. Saving Tomorrow's Agricultural Resources (STAR). https://starfreetool.com/home.

315   State of Maryland. Plan for Growing 5 Million Trees https://mde.maryland.gov/programs/air/ClimateChange/SiteAssets/Pages/Trees-Commission/DRAFT%20Plan%20for%20Growing%205%20Million%20Trees%20in%20Maryland.pdf

316   Townsend, J., Moola, F. & Craig, M.-K. J. F. Indigenous Peoples are critical to the success of nature-based solutions to climate change. *Facets* 5, 551-556 (2020).

317   Garnett, S. T. *et al.* A spatial overview of the global importance of Indigenous lands for conservation. *Nature Sustainability* 1, 369-374 (2018).

318   Abrams, M. D. Fire and the development of oak forests. *BioScience* 42, 346-353 (1992).

319   Guyette, R. P., Muzika, R.-M. & Dey, D. C. Dynamics of an anthropogenic fire regime. *Ecosystems* 5, 472-486 (2002).

320   Abrams, M. D., Nowacki, G. Examining the heritage and legacy of Indigenous land management in oak and pine forests of northeastern United States. *International Journal of Ecology and Environmental Sciences* 47, 27-36 (2021).

321   Fleischman, F. *et al.* How politics shapes the outcomes of forest carbon finance. *Current Opinion in Environmental Sustainability* 51, 7-14 (2021).

322   Osaka, S., Bellamy, R. & Castree, N. Framing "nature-based" solutions to climate change. *Wiley Interdisciplinary Reviews: Climate Change* 12, e729 (2021).

323   Seddon, N. *et al.* Getting the message right on nature-based solutions to climate change. *Global Change Biology* 27, 1518-1546 (2021).

324   Bremer, L. L., Keeler, B., Pascua, P., Walker, R. & Sterling, E. Nature-based solutions, sustainable development, and equity. In *Nature-based Solutions and Water Security*, 81-105. Elsevier. (2021).

325   The Justice40 Initiative. https://www.thejustice40.com/