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

Summary Report

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Rationale and objectives

The impacts of climate change are accelerating with devastating consequences, and addressing the climate crisis is fundamental for the national interest and societal well-being. **The scientific consensus on how to solve the climate change crisis is clear: we need to dramatically reduce and eliminate anthropogenic emissions of greenhouse gases (GHGs) from fossil fuel burning[1].** However, given the slow pace of mitigation so far, emission reductions alone will likely be insufficient to prevent dangerously high levels of warming, and they will need to be complemented with approaches for removing CO_2 directly from the atmosphere[2]. One way to do this is with **Nature-based Climate Solutions (or NbCS),** which are managed alterations to ecosystems designed to increase atmospheric CO_2 sequestration or to reduce emissions of GHGs[3-8]. NbCS are not a panacea for climate change, and can only be effective when they are pursued concurrently with rapid decarbonization. **Nonetheless, NbCS are part of most pathways to limit warming to <1.5 ºC[9].** Unlike other CO_2 removal strategies, **NbCS confer well-known co-benefits** for biodiversity, air and water quality, and soil health[3,7,8], and many have adaptive benefits that enhance ecosystem resilience to climate change[4,6,7,10].

This report focuses on land-based NbCS strategies, which can be classified into those applicable to forests, to working lands like croplands and grasslands, and to terrestrial wetlands (Fig. 1), with some hybrid approaches blending elements of nature-based and engineered carbon removal[11]. Briefly, forest-based strategies like reforestation, avoided deforestation, and improved forest management tend to be associated with high but uncertain mitigation potentials, and with substantial uncertainty surrounding the durability of carbon stored in biomass that is vulnerable to fire, insects, and drought stress[12,13]. Agricultural strategies like cover cropping, biochar addition, and enhanced rock weathering may represent the lowest hanging fruit for NbCS, as they can be implemented in landscapes that are already intensely managed. However, many questions remain about their effectiveness in working lands that span wide gradients of climate, soils, and management regimes[14-16]. Wetland strategies, including restoration and avoided wetland conversion, often require consideration of tradeoffs between carbon storage and emissions of non-CO_2 GHGs. All terrestrial NbCS are also sensitive to socio-economic factors that inform landowner decisions about management practices, which can strongly affect whether NbCS efforts lead to additional climate benefits beyond the baseline.

NbCS have strong and growing interest from a unique coalition of actors, including bipartisan lawmakers, conservation groups, the private sector, and many federal and state agencies. At the federal level, tens of billions of dollars are being allocated to NbCS through the recently enacted Inflation Reduction Act and Executive Order 14072. At the state level, cap-and-trade policies administered by the California Air Resources Board have fueled compliance market activity amount to millions of nature-based offset credits valued at billions of dollars[17]. In the private sector, voluntary carbon markets have experienced significant growth in the last 2-3 years, trading $1 billion in offsets in 2021[18]. At the same time, NbCS are being rigorously evaluated by broad consortia of university, NGO, and public sector scientists[3,5,6,19-25], and criticism of offset programs in particular is motivating the development of next-generation strategies for incentivizing and monitoring NbCS projects[26,27]. Taken together, there is every indication that NbCS will be a core component 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 meet **four essential criteria:**

Criteria 1: Lead to **enhancements to carbon uptake and/or reduced emissions of non-CO_2 GHGs that are additional** to a baseline scenario, and that integrate over all ecosystem sources and sinks.

Criteria 2: Lead to a **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 durability** by accounting for social and environmental risks to the permanence of ecosystem carbon storage and avoided emissions.

Criteria 4: **Account for leakage** so that gains in one area are not canceled out by shifting activities to another area.

As discussed in detail in this report and elsewhere[4,6,17,20,25,28,29], **the extent to which NbCS meet these key criteria is highly uncertain.** At regional and continental scales most relevant to policy-setting, estimates of NbCS mitigation potential 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 pools: shallow soil and aboveground plant biomass. Alone, a focus on these two pools 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 pools change are sparse and unrepresentative of naturally occurring environmental gradients, limiting our ability to quantify baselines against which additionality can be calculated (criteria 1). Carbon stock changes also do not capture "biophysical" impacts of NbCS that can have both favorable and unintended direct effects on temperature and water cycling (criteria 2). Finally, 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.** The important role of terrestrial ecosystems in determining atmospheric CO_2 concentrations is well-established[30], and over decades, huge investments of material resources have fostered innovative measurement technologies, analytical tools, and predictive models for quantifying ecosystem carbon cycles (Fig. 2). These tools have historically been used for basic research and the vast majority have not been fully leveraged for what they reveal about expected and realized benefits of NbCS[6]. 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, as we face a sea change in federal and private-sector spending on NbCS, **we have a unique opportunity to integrate the best available science into next-generation information systems** to support NbCS that address all four key criteria.

The objective of this report is to describe the technologies, tools and approaches necessary for robust, scalable, and credible NbCS in the United States (Box 1). We aim to provide a road map for **actionable, cross-sectoral data and information to foster strategies that work,** and to avoid energy wasted on those that do not. We begin by highlighting specific knowledge gaps. We then describe pathways for closing them with a national NbCS "Information Network" that integrates the best-available tools and technologies (Fig. 2) to inform NbCS program design and to support rigorous monitoring, verification, and reporting. In many cases, 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 resource investment necessary to address these knowledge gaps. While this report focuses primarily on the technical mitigation potential of NbCS, whenever possible, we highlight opportunities to better understand the socio-economic factors that determine the realizable potential of NbCS on the ground.

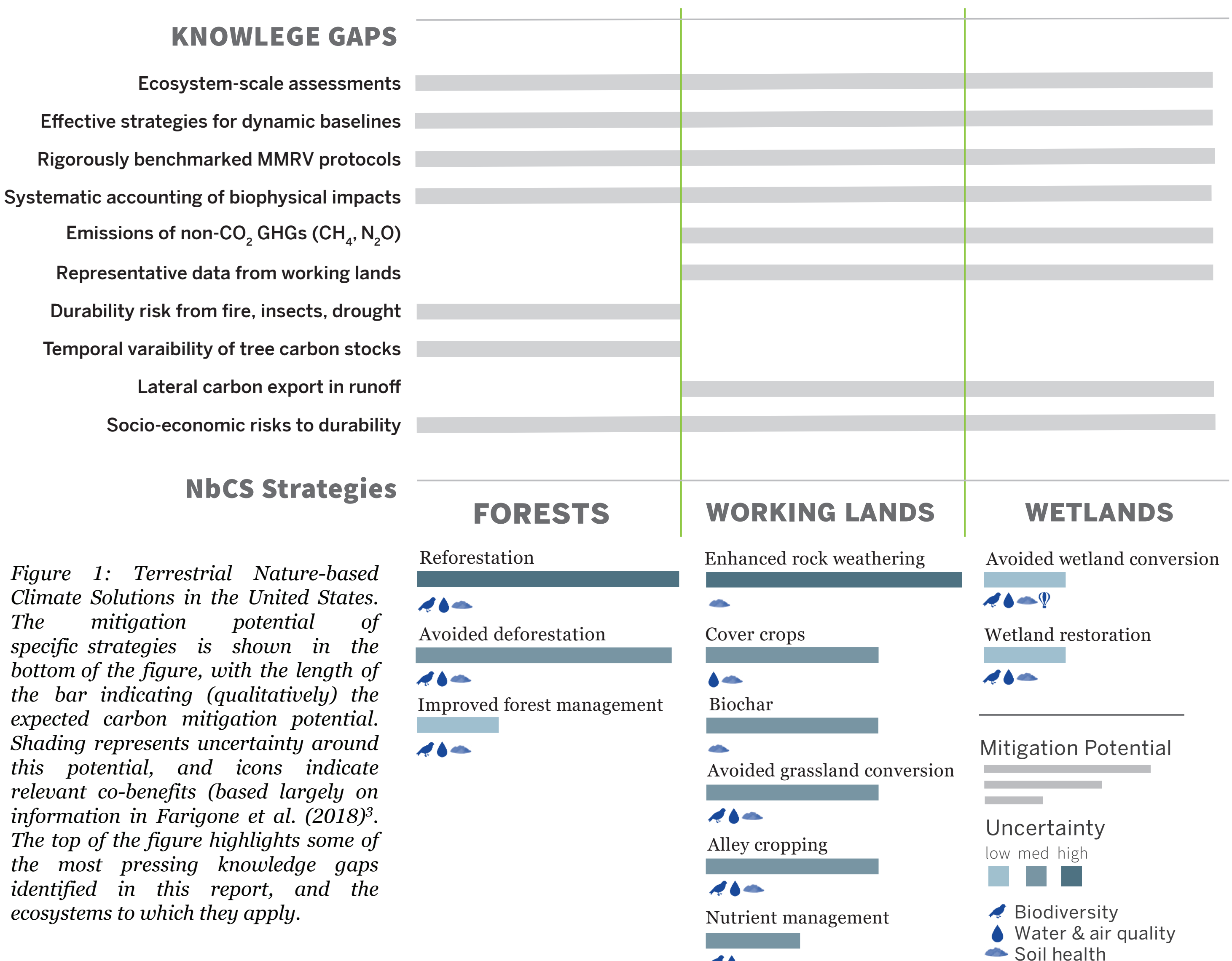

Figure 1: Terrestrial Nature-based Climate Solutions in the United States. The mitigation potential of specific strategies is shown in the bottom of the figure, with the length of the bar indicating (qualitatively) the expected carbon mitigation potential. Shading represents uncertainty around this potential, and icons indicate relevant co-benefits (based largely on information in Farigone et al. (2018)[3]. The top of the figure highlights some of the most pressing knowledge gaps identified in this report, and the ecosystems to which they apply.

BOX 1: Elements of Robust, Scalable and Credible NbCS

ROBUST: NbCS incentivization programs fully address all four key criteria of success (additional mitigation, net cooling, durability, and leakage). Doing so means that NbCS accounting schemes are 1) 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.

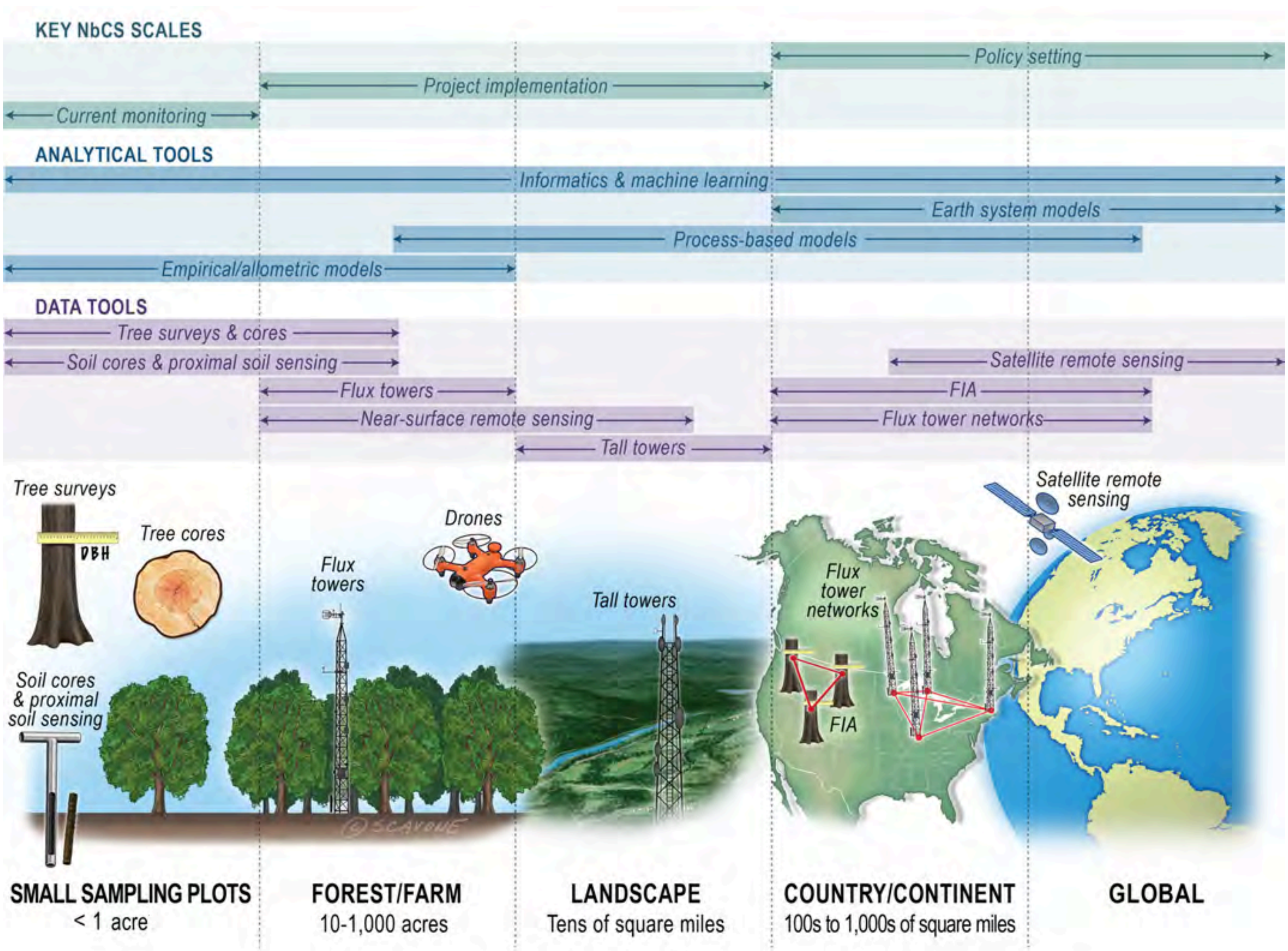

Figure 2: The data and analytical tools that could be more fully leveraged to inform NbCS. See Box 3 for details.

Key Knowledge Gaps

2.1 Knowledge gaps related to field data availability. While networks like AmeriFlux[31], NEON[32], and FIA[33] are providing a wealth of information about ecosystem carbon cycles, they were not designed specifically with the goal of studying NbCS. Many NbCS strategies (e.g., cover crops, soil amendments, altered forest management) are under-represented in these networks, and no single network reports all relevant data necessary for robust evaluations. Particularly in agricultural systems, a lack of representative data describing spatial and temporal patterns of soil carbon, nutrient dynamics, and GHG emissions limits consensus about the degree to which agricultural NbCS can mitigate climate change[14,15,34]. In wetlands and some croplands, we lack the data necessary to understand the amount and fate of carbon lost through runoff. In forests, rich information about aboveground tree biomass is available from FIA and remote sensing[35]; however, long resampling intervals, and limited data on soil carbon, dead wood pools, and disturbance agents prevent robust understanding of carbon benefits and their durability.

2.2 Knowledge gaps related to a historic emphasis on a limited set of carbon pools. Until now, NbCS benefits have focused on two slowly evolving carbon pools (or stocks): [1] carbon stored in the top 30 cm of the soil in croplands and grasslands, and [2] the carbon contained in aboveground plant biomass, which is usually the only pool considered in assessments of forest-based NbCS. A narrow focus on these two pools misses important carbon sources and sinks, biasing our understanding of NbCS impacts at the ecosystem scale. Soils store a large proportion of carbon at depths >30 cm, and failure to monitor deep soil carbon pools can lead to uncertain or overly optimistic assessments of NbCS impacts[36-38]. For forests, changes in stem growth are not always coupled with net ecosystem carbon uptake[39-42], and the focus on aboveground biomass neglects forest soil carbon and dead wood pools, which can be large and dynamic. In all cases, since ecosystem carbon pools are quite large to begin with, it can take years for a change in these pools to become detectable[6]. Finally, changes in soil and biomass carbon alone can not tell us much about how NbCS impact emissions of methane or nitrous oxide.

2.3 Knowledge gaps preventing spatial mapping of NbCS mitigation potentials: The most robust NbCS programs would be designed with an understanding of where and when a given strategy is most likely to succeed. Unfortunately, maps of climate mitigation potentials for most NbCS strategies are scarce. This is especially true for agricultural and wetland NbCS, which are characterized by a lack of representative data that spans many axes of variability (soils, climate, species, historic management[43,44]). Mitigation potential maps of forest-based strategies – and especially reforestation – are relatively abundant[22], thanks to a wealth of data on aboveground biomass provided by forest inventory data and complemented with remote-sensed proxies for forest biomass.[35] However, these maps tend to focus on changes in aboveground tree biomass only, neglecting other pools.

2.4 Knowledge gaps preventing a holistic assessment of NbCS biophysical impacts: Any intervention that affects carbon cycling will have concurrent "biophysical impacts" on local water and energy cycling, as these three cycles are closely coupled. For example, greater photosynthesis is usually accompanied by greater evapotranspiration[45,46] which will tend to decrease soil moisture and runoff. Likewise, land cover shifts can affect temperature directly, through the combined impacts of alterations to surface albedo (or brightness) and evaporative and sensible heat exchanges[47,48]. For some categories of NbCS – especially reforestation and avoided deforestation – our understanding of the biophysical impacts on surface temperature is relatively well advanced[49,50]. We know that tropical and temperate zone reforestation tends to have a surface cooling effect, but boreal zone reforestation tends to promote surface warming[48,49,51]. However, with some exceptions[52], biophysical impacts of most NbCS have not been rigorously quantified, and more work is necessary to understand NbCS impacts on air temperature[53,54] and to improve model predictions for how land cover change in one area may drive biophysical impacts in another[55,56].

2.5: Knowledge gaps limiting our ability to predict the durability of ecosystem carbon: Durability refers to the period of time over which carbon removals or avoided emissions persist without failure. Long-lasting durability is essential whenever NbCS are used to offset or otherwise justify CO_2 emissions. It depends on physical risk factors that can lead to "reversals" by which carbon returns back to the atmosphere – for example, widespread tree mortality driven by fire, drought, and insect outbreaks[12,13], or respiration of soil carbon stored in unprotected forms. Durability also depends on program governance features, such as whether a parcel of land has committed to maintain climate-friendly practices by contract or by easement. Today, most NbCS accounting systems do not feature significant recognition of this issue. There is an urgent need to understand the absolute permanence risks from both climate and socio-economic forcings, and to develop frameworks for incorporating them into NbCS accounting protocols. Closing this gap requires ecosystem models featuring robust representation of NbCS-relevant mechanisms at NbCS-relevant scales, and which can be integrated with information about socio-economic factors that influence landowner decisions about practice adoption and abandonment.

2.6 Additional knowledge gaps that hinder credible accounting of NbCS projects. Historically, the compliance and voluntary carbon markets used to incentivize NbCS activities have centered on carbon credits and offsets. Credibility of these programs requires reliable and accurate data, and transparent monitoring and verification protocols that can be evaluated and replicated by objective third parties. However, these protocols vary substantially from one market entity to the next, and lack rigorous cross-comparison and standardization. These shortcomings limit the system-wide equivalency of carbon credits, and erode confidence in the quality of carbon offsets. Moreover, NbCS accounting schemes require a demonstration of additionality over a "business-as-usual" baseline approach. Right now, baselines are modeled or estimated indirectly and may not represent reality. Dynamic and data-driven baselines could reduce some of this uncertainty, enabled through pairwise matching of a project to control areas in the field, or by integrating remote-sensing and field data into dynamic baseline maps that may also offer tools for assessing leakage. As the next-generation of NbCS accounting protocols develop, there will be a need for mechanisms to "sunset" problematic past practices.

BOX 2: Summary of knowledge gaps preventing robust, scalable and credible NbCS in the United States

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 disturbances such as wildfire may be incompletely captured with a distributed plot sampling network.

KNOWLEDGE GAPS RELATED TO A HISTORIC EMPHASIS ON A LIMITED SET OF CARBON POOLS

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 understanding of NbCS impacts on methane and nitrous oxide emissions.

KNOWLEDGE GAPS PREVENTING POLICY-RELEVANT MAPPING OF NBCS MITIGATION POTENTIALS

Gap 2.3a: Especially in agricultural and wetland systems, we lack maps of NbCS mitigation potentials, preventing an understanding of when and where these strategies are most likely to succeed.
Gap 2.3b: In forests, existing potential maps are primarily informed by data on tree biomass change, which miss other important carbon pools.

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.

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.
Gab 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

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.

An Information Network for Robust, Scalable, and Credible Nature-based Climate Solutions

Coordinated investment in a national NbCS "Information Network" (Fig. 3, Table 1) could provide the data and derived products necessary to close these knowledge gaps, fostering robust, scalable and credible NbCS strategies. Specific recommended network activities include enhancing and expanding ground-based monitoring networks and distributed experiments, integrating satellite data into scalable maps and models, and rigorously benchmarking protocols for project-scale accounting. To be most useful, these activities should be informed by centrally-developed guidelines and best practices, supported by cyberinfrastructure for open and interoperable sharing of data and derived products, and complemented by an information "service" to encourage bidirectional outreach and feedback from a wide range of end-users.

Fortunately, the carbon cycle research community has a long history of network-enabled information sharing, spanning a gradient of coalition-driven, bottom up networks which enable nimble responses to emerging research needs (e.g. AmeriFlux[31], the USDA LTAR program[57], and NSF's LTER[58] and CZO programs[59]) and top-down, centralized initiatives like NEON[32] and FIA[33] which produce highly standardized data products but with reduced flexibility. 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 research networks.** A centralized task that solicits cross-sector input, sets measurement priorities, and guides cyberinfrastructure development and stakeholder engagement, is foundational for the production of robust, scalable, and usable information. Field campaigns, mapping and modeling exercises, and protocol evaluations conducted in a more bottom-up way would permit efficient leveraging of existing research infrastructure and collaborative teams.

The biggest value of the network activities is through their integrated and coordinated execution – the whole is greater than the sum of the parts. Verification and transparency are critical for the success of any mitigation program, and fortunately, many of the needed technologies and tools to develop robust, scalable and credible NbCS policy are already available and tested. Nonetheless, the investment necessary to fully realize the vision of this network is sizable (~$1 billion USD over 5 years), though it is substantially less than the 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.

3.1 A centralized task force for priority setting, data standards, and data delivery. There is a need for an inter-agency and cross-sectoral task force to: [1] create a dynamic inventory of existing NbCS field trials and monitoring initiatives to identify gaps and to set priorities for field campaigns, [2] create best practices for NbCS field data collection, including measurement standards, sampling design, and metadata collection, and [3] guide development of cyberinfrastructure for inter-operable delivery of field data, remote sensing products, and derived products like maps, model forecasts, and code. This task force would benefit from diverse stakeholder input, including federal agencies, university researchers, NGOs, the private sector, Indigenous leaders, and agencies that represent landowners.

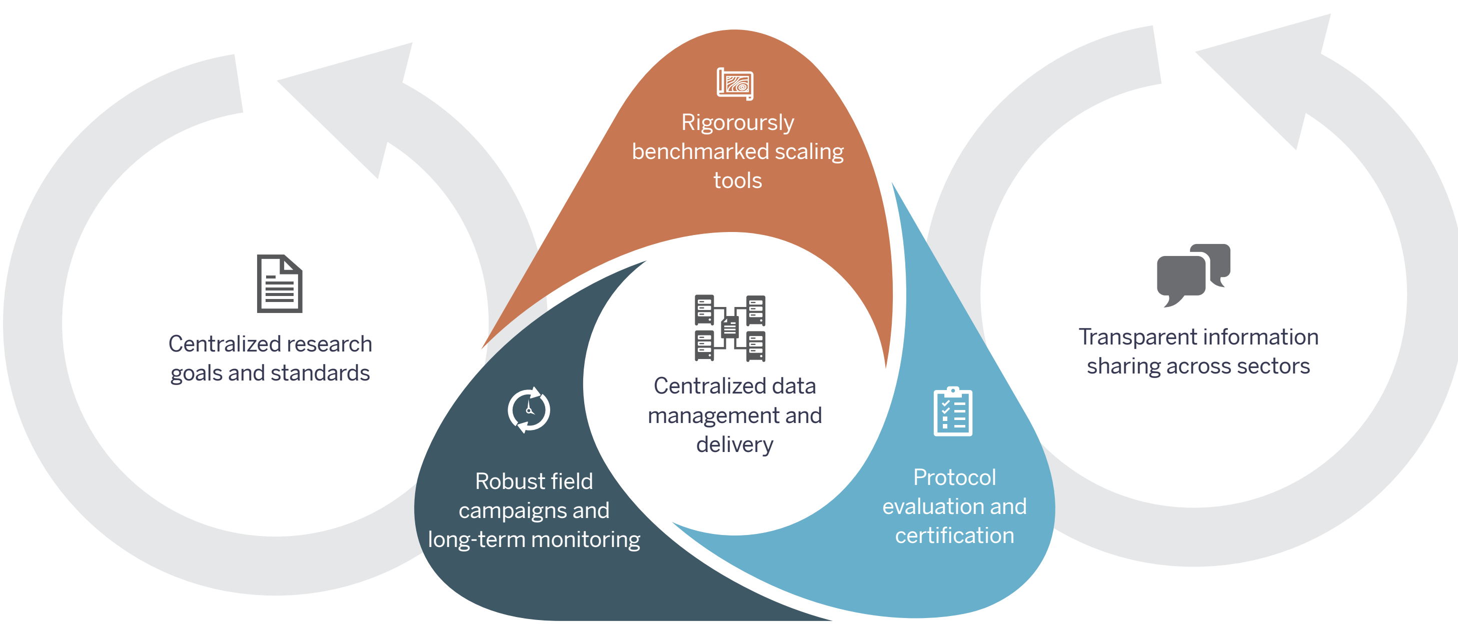

Figure 3: Core components of a National NbCS Information Network

3.2 Robust ground-based monitoring and experimentation: Many of the knowledge gaps identified in Section 2 can not be systematically addressed without more robust and representative data. The material investment required to achieve this goal could be greatly reduced by leveraging existing physical infrastructure supported by networks like AmeriFlux, LTAR, LTER, FIA, and NEON, through activities that include:

Gold standard datasets providing extensive information about site-level NbCS impacts using most of the tools in Fig. 2 (e.g. extensive carbon pool monitoring, flux towers, tree cores, proximal soil sensing, near surface remote sensing). Gold standard datasets from paired sites (an NbCS treatment and a co-located baseline control) would be especially useful for: [1] pilot testing understudied NbCS strategies, [2] robust understanding of coupled NbCS impacts on carbon, water, and energy cycle pools and fluxes, [3] evaluating and certifying crediting protocols, and [4] benchmarking remote sensing products and models.

Distributed and coordinated experiments and field trials to evaluate the potential of emerging or understudied NbCS (e.g. biochar, enhanced crop weathering, alley cropping, wetland restoration). While some of these experiments and field trials could generate gold-standard datasets, to increase representativeness in a cost-effective way, others could focus on a more limited set of observables.

Sustaining and expanding flux tower networks so that they better represent baseline treatments and controls, and so that some sites are augmented with additional variables (soil carbon sampling, forest biomass sampling, tree cores) to enable more robust interpretation of what these network data reveal about NbCS, and to facilitate scaling exercises discussed in Section 3.3.

Enhancing Forest Inventory Networks like FIA to include: [1] routine monitoring of carbon in soils, dead wood, and litter pools, [2] data describing interannual variability in growth using tree rings or more frequent sampling, [3] better documentation of mortality agents and the growth of small trees, and [4] the development of scaling tools describing forest structure over areas that are better matched to the resolution of satellites. These amendments would enable more robust and timely quantification of forest NbCS impacts and disturbance risks, and would provide more robust information for scaling exercises.

A new national soil carbon monitoring network providing repeat monitoring of soil carbon and nutrient pool dynamics across multiple depths, and across sites that span broadly representative gradients of management regime, climate, and soil type. This network would provide critically needed baseline data against which the realized benefits of NbCS projects could be compared[60]. It would also greatly expand the datasets that can be ingested into predictive models for calibration and validation, and for integrating with scaling tools for mitigation potential and baseline mapping.

3.3 Rigorously benchmarked scaling tools: Blending robust ground-based observations with next-generation remote sensing products could enable mapping of NbCS mitigation potentials at policy relevant scales, so that NbCS strategies could be incentivized most strongly where they are most likely to succeed. Moreover, flux towers and many remote-sensing platforms also provide information about ecosystem evapotranspiration, soil moisture, and surface temperature, affording opportunities to map the biophysical impacts of NbCS along with their carbon mitigation potentials. Similar strategies could be used to generate dynamic baseline maps (driven by flux measurements, stock measurements, or both) using both traditional regression-based models as well as emerging approaches for machine-learning upscaling[61,62]. Wall-to-wall, dynamic maps of forest biomass and soil carbon that are cross-comparable at a relatively high spatial resolution would be useful not only for baseline mapping, but also for durability quantification (especially when blended with wall-to-wall disturbance risk maps), and leakage assessments (especially when evaluated together with socio-economic modeling tools). Finally, the most robust durability assessments require mechanistic ecosystem models capable of predicting NbCS impacts into a future characterized by multiple climate feedbacks. Continued investment to represent NbCS-relevant management in ecosystem models at appropriate scales, should be a priority.

3.4 Protocol evaluation and certification: Regardless of the policy instrument used to incentivize NbCS, scalable and credible implementation will require strategies for monitoring and verifying the realized benefits of individual NbCS projects. An immediate research opportunity is the systematic and centralized inter-comparison of the accounting protocols currently used within carbon markets and other incentivization programs (sometimes referred to as protocols for "Measurement, Monitoring, Reporting and Verification," or MMRV). A particularly robust inter-comparison could rely on the gold-standard NbCS datasets, though a comparison of crediting protocols against predictions from more mechanistic models would also be valuable. Eventually, a given protocol's success in quantifying observed gold-standard flux and stock changes (to some acceptable level of uncertainty) could be used to represent a credibility standard justifying its use in publicly-supported, "climate-smart" programs. Next, a critical element of nearly all project-specific accounting schemes is the benchmarking of additional benefits against a business-as-usual baseline. Evaluating the usefulness of dynamic regional baseline maps, or project-scale baselines generated with pairwise treatment-control schemes, is an important information need. Regional, dynamic baseline maps could also be interrogated for the extent to which they reduce adverse selection and provide information about leakage. Finally, there remains a need for accessible models that are capable of robust durability predictions.

Table 1

Initiatives that can close knowledge gaps to support robust, scalable, and credible NbCS, especially as part of a national NbCS Information Network. Refer to Box 2 for knowledge gap codes. Interpretation of the hourglass icons is as follows:

achievable on a rapid timeline (e.g. <1 year),

some aspects achievable immediately, but others may require more time

some aspects achievable on 2-3 year horizons, with others achievable over longer timescales.

Interpretation of the cost icons are as follows: $ = 10 million USD, $$ = 10-50 million USD, $$$ = 50-100 million USD, and $$$$ = >100 million USD. These costs represent the combined capital investment and operation costs for a five-year period. The "" indicates that the success of the initiative relies on sufficiently representative field data, which requires investment in the robust ground-monitoring initiatives. These represent rough estimates informed by publicly available information about the budgets of existing environmental observation networks, data science centers, and modeling and mapping initiatives.*

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.	$$
Summary of robust ground monitoring initiatives				
Gold-standard datasets in paired and long-term monitoring sites.	2.1a,c 2.2a,b,c 2.4a,b,c2.6a,b	Individual research teams working with existing network hubs, guided by centralized best practices.	Robust evaluation of emerging or understudied NbCS strategies. Rigorously compare and evaluate protocols for crediting & accounting. Benchmark remote sensing products and models Improve mechanistic understanding of NbCS. impacts and explore data biases.	$$$$
Distributed experiments and field trials	2.1a,b,c 2.2c 2.3a,b	Same as above	Replicated evaluation of emerging or understudied NbCS strategies. Permit benchmarking of models and remote sensing across broader gradients. Generate representative data required for potential mapping and dynamic baselines.	$$$
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	$$$$
Summary of scaling initiatives				
Regional-scale mapping of **NbCS potentials & expected biophysical impacts**	2.3a,b 2.4a,b,c	Individual research teams guided by centralized best practices.	Provide robust, policy-relevant information on where specific NbCS strategies are most likely to succeed as climate mitigation tools. Anticipate opportunities for climate adaptation, and avoid unintended biophysical consequences.	$$*
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.	$$*
Wall-to-wall, dynamic, **high-res forest biomass and soil carbon maps.**	2.3a,b 2.5b 2.6a,b,c	Same as above	Baseline mapping, leakage detection, and protocol evaluation. Understanding the gap between technical and realizable mitigation potential.	$*
Wall-to-wall **forest disturbance risk maps**	2.5a,b,c 2.6c	Same as above	Understand spatial and temporal variability in durability risks associated with forest NbCS.	$$*
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.	$$*
Summary of protocol evaluation and certification initiatives				
Systematic cross-comparison of protocols for project-scale crediting, monitoring, and verification	2.6a	Individual research teams working closely with federal and private stakeholders	Understand the extent to which carbon credits are interoperable. Provide a mechanism for certifying climate-smart commodities. Increase trust in NbCS incentivization programs.	$$*
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.	$$*
Make predictive models more accessible to non-experts	2.5c 2.6a,b,c	Same as above	Inform the development of NbCS incentivization programs that favor strategies in the places they are most likely to succeed.	$$*

Timelines, Uncertainty, and Socio-economic considerations

There is misalignment between the pace at which NbCS programs are being funded, and the pace at which the science necessary to inform robust, scalable, and credible programs can be generated. The opportunity to leverage pre-existing research infrastructure and networks could enable many of the information products summarized in Table 1 to be delivered on time scales of 1-3 years. Nonetheless, private- and public-sector NbCS initiatives may produce substantial investment in NbCS projects sooner than that. Thus, it is critical that we rapidly prioritize investment in the research necessary to close existing NbCS knowledge gaps while designing flexible incentivization and monitoring programs that are capable of assimilating the best-available science as it becomes more readily available.

It is also important to recognize that the scientific community has not reached consensus on the realizable climate benefits of Nature-based Climate Solutions[6,7,13,19,20], and on how aggressively they should be pursued. 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 authors of this report **unanimously agree that the most effective climate mitigation tools are those that reduce emissions of greenhouse gases from fossil fuel burning**. While NbCS can provide important additional mitigation, nature-based strategies cannot be successful if they are not pursued concurrently with economy-wide decarbonization. Next, there is broad-scale agreement that **many NbCS pathways advantage landowners and the environment through co-benefits** linked to soil health, biodiversity, and air and water quality. There is agreement that we should incentivize those practices using a wide range of tools based on this holistic set of benefits, while being careful about their promotion as climate solutions until their mitigation potential is clearly established.

There is also broad-scale agreement that GHG reductions are critical components of robust NbCS for agricultural and wetland systems. However, the existing set of NbCS incentivization tools have tended to focus only on carbon removals; both are important to consider to meet the criteria for robustness. Finally, there was strong agreement among participants in the workshop that the challenges of accounting for carbon sequestration, now and in the future, create significant risks for using any generated credits as offsets for anthropogenic emissions.

While this report largely focuses on the information needed to assess the technical mitigation potential of NbCS (e.g., the maximum mitigation that is theoretically achievable), we recognize that many other socio-economic factors will cause the "realizable" potential to be lower than this upper-bound maximum. Research on the socio-economic factors that determine landowner decision-making and equitable implementation, coupled with bidirectional outreach and education between scientists and stakeholders, are critical elements of successful NbCS programs, and to an extent that may not be fully expressed in this report. Moreover, while our report was organized around a federal perspective, **state governments, Tribal leaders, 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 for ensuring that the research activities described in this document provide information that is actually used in practice, as opposed to merely being theoretically useful.

BOX 3: The Best-Available science.

Here, we summarize the measurement technologies and analytical tools that have emerged from decades of research on ecosystem carbon cycling (as illustrated in Figure 2). The vast majority of these tools have not yet been fully leveraged for what they can tell us about the potential and impacts of NbCS in the United States.

REPEAT FIELD MEASUREMENTS OF CARBON STOCKS, including soil organic carbon and the carbon contained in plant biomass, are critical for monitoring changes in how these carbon pools change over time, and form the basis for most existing NbCS potential estimates and accounting protocols[3,24,26].

FLUX TOWERS AND FLUX TOWER NETWORKS permit continuous, ecosystem-scale observation of the movement of greenhouse gases, water, and energy between ecosystems and the atmosphere[63]. Long-term records from hundreds of flux towers in the United States are already widely accessible through networks like AmeriFlux[31] and NEON[32]. The high temporal resolution of flux data permits rapid evaluation of NbCS impacts on net land-atmosphere GHG, water and energy fluxes.

THE USDA FOREST INVENTORY AND ANALYSIS (FIA) PROGRAM[33] and related state- and tribal-level initiatives provide invaluable information about forest carbon stocks and a host of forest health indicators at the national scale, through plot-level surveys repeated every 5-10 years.

PROXIMAL SOIL SENSING[64-66] of soil carbon stocks and other critical soil properties, has the potential to greatly increase the acquisition of soil data at significantly reduced costs.

TREE CORES, which have a rich history of use as proxies for historic climate, can provide information about annual changes in tree biomass that could constrain estimates of future tree growth and associated carbon storage[67,68].

NEXT-GENERATION SATELLITE REMOTE SENSING PRODUCTS including recent and planned space and airborne missions such as the Orbital Carbon Observatories[69,70,] the Global Ecosystem Dynamics Investigation (GEDI)[71], ECOSTRESS[72], MODIS[73], and multiple platforms for microwave remote sensing of vegetative water content[74] now provide wall-to-wall information about both ecosystem structure and function (so-called "Flux towers in the sky"[75]).

EMPIRICAL AND ALLOMETRIC MODELS, including regression-based models as well as standardized equations to convert measurements of tree size into estimates of biomass carbon, have long played a central role in NbCS accounting.

PROCESS-BASED MODELS tend to prescribe the relationships between environmental drivers and ecosystems responses on the basis of theoretical laws and principles, which should make them better suited for extrapolation across space and into the future.

EARTH SYSTEM MODELS, capable of predicting how ecosystems will respond to future climate feedbacks, are sophisticated tools that hitherto have been primarily used to understand global patterns of land carbon uptake.

INFORMATICS AND MACHINE LEARNING are becoming increasingly important tools for understanding large and growing amounts of information about local to global ecosystem function. While fundamentally empirical in nature, many machine learning approaches can be blended with process-based models and they do not require *a priori* assumptions about how variables are related.

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