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Informing Nature-based Climate Solutions for the U.S. with the best-available science

Running title: *Informing Nature-based Climate Solutions*

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Abstract: Nature-based Climate Solutions (NbCS) are managed alterations to ecosystems designed to increase carbon sequestration or reduce greenhouse gas emissions. While they have growing public and private support, the realizable benefits and unintended consequences of NbCS are not well understood. At regional scales where policy decisions are often made, NbCS benefits are estimated from soil and tree survey data that can miss important carbon sources and sinks within an ecosystem, and do not reveal the biophysical impacts of NbCS for local water and energy cycles. The only direct observations of ecosystem-scale carbon fluxes, e.g., by eddy covariance flux towers, have not yet been systematically assessed for what they can tell us about NbCS potentials, and state-of-the-art remote sensing products and land-surface models are not yet being widely used to inform NbCS policy making or implementation. As a result, there is a critical mismatch between the point- and tree- scale data most often used to assess NbCS benefits and impacts, the ecosystem and landscape scales where NbCS projects are implemented, and the regional to continental scales most relevant to policy making. Here, we propose a research agenda to confront these gaps using data and tools that have long been used to understand the mechanisms driving ecosystem carbon and energy cycling, but have not yet been widely applied to NbCS. We outline steps for creating robust NbCS assessments at both local to regional scales that are informed by ecosystem-scale observations, and which consider concurrent biophysical impacts, future climate feedbacks, and the need for equitable and inclusive NbCS implementation strategies. We contend that these research goals can largely be accomplished by shifting the scales at which pre-existing tools are applied and blended together, although we also highlight some opportunities for more radical shifts in approach.

Keywords: Natural climate solutions, climate mitigation, net-zero, ecosystem carbon cycling, climate adaptation

1. Overview:

Terrestrial ecosystems, which sequester about a third of anthropogenic CO_2 emissions (Friedlingstein et al. 2020), have long been studied for their outsized role in mitigating the pace of climate warming (Baldocchi 2001, Churkina & Running 1998, Torn & Chapin 1993). As climate change impacts become more pronounced, and the need to remove CO_2 from the atmosphere becomes more urgent, support is growing for the notion that ecosystems could be actively managed to increase carbon sequestration or reduce greenhouse gas (GHG) emissions (Griscom et al. 2017, Nolan et al. 2021, Seddon et al. 2020). These Nature-based Climate Solutions (NbCS) are not a panacea for climate change mitigation (Anderson et al. 2019); and absolutely cannot be effective without concurrent and dramatic economy-wide decarbonization. Even in the best-case scenarios, NbCS will contribute only a fraction of the remissions reductions necessary to limit warming to <2 ^{o}C. Nonetheless, removing CO_2 from the atmosphere is part of nearly all net-zero pathways (IPCC 2018), and NbCS may offer low-cost mitigation along with co-benefits such as improved air and water quality, better soil health, biodiversity maintenance (Fargione et al. 2018) and local climate adaptation (Osaka et al. 2021).

In the U.S., intentional implementation of NbCS has been relatively limited, and largely organized around private volunatry carbon markets (Anderegg 2021, Seddon et al. 2021, but see CNRA 2021), which offer the promise of revenue streams for landowners and for private entities focused on project development and monitoring. Forest carbon offset projects in California's compliance system perhaps represent a more systematic attempt at coordinated NbCS implementation (Anderegg et al. 2020), though the actual mitigation achieved through these projects is not clear (Badgley et al. 2021). However, looking forward, state- and federal agencies appear poised to authorize large investments in NbCS programs (Fargione et al. 2019, Fleishman et al. 2020, Seddon et al. 2020a). For example, the U.S. Senate passed the "Growing Climate Solutions Act" in 2021, and in early 2022, the USDA released a $1 billion call for proposals for "Climate-Smart Commodities." Indeed, it is an unusual coalition, including conservation groups, farmers, foresters, bipartisan groups of lawmakers, and private start-ups and industry, that is driving momentum in the NbCS sphere.

Despite this enthusiasm, the realizable benefits of NbCS are not well understood and often difficult to quantify (Seddon et al. 2020a). They are usually estimated as a change in carbon stocks determined from biometric soil or tree survey data (Griscom et al. 2017, Cook-Patton et al. 2020). These surveys, however, can miss changes in stocks that are unmeasured or hidden by landscape heterogeneity, and do not provide information about methane and nitrous oxide emissions or concurrent biophysical impacts on temperature and water cycling. Moreover, for many NbCS, existing biometric data are sparse and unrepresentative of naturally occurring gradients in soil and climate. As a result, there is a critical mismatch in scale between the biometric data most often used in NbCS accounting, the ecosystem and landscape scales where NbCS projects are implemented, and the regional to continental scales at which relevant policies are developed.

The situation becomes even more poorly constrained looking forward, when climate-driven feedbacks threaten the permanence of carbon stored in many ecosystems. In forests, the large amount of carbon stored in aboveground plant biomass is threatened by increasing drought, wildfires, and insect outbreaks (Anderegg et al. 2020, Coffield et al. 2021); in soils, warming can stimulate decomposition and CO_2 fluxes (Hicks Pries et al. 2017). The Earth System Models (ESMs, Heavens et al. 2013) used to couple interactions between ecosystems and the climate system account for these feedbacks, but the simpler models used for NbCS benefit evaluation do not. Finally, all this uncertainty propagates into operational barriers hindering NbCS project implementation within carbon markets. That process generally relies on statistical models and biometric soil and tree survey data collected over relatively long timescales (typically 5+ years). The resource-intensive nature of biometric inventories, along with the relatively low price of carbon, practically excludes all but the largest non-tenant producers and landowners from participating. The approach also exposes the system to risks associated with unduly optimistic assessments of project benefits or practice implementation (Badgley et al. 2021).

Our objective is to identify knowledge gaps surrounding NbCS that may be confronted, over the short term, with pre-existing data, infrastructure, and tools that have long been used to measure and predict ecosystem-scale GHG exchanges, but have not yet been harnessed for what they reveal about NbCS effectiveness. We contend that new perspectives on NbCS climate benefits and unintended consequences can be largely enabled by relatively subtle shifts in the scales at which these existing tools are applied (e.g., “modular innovation”) and blended together (e.g. “architectural innovation, *sensu* Henderson et al. 1990, see Figure 1). However, for some uncertainties, and especially those surrounding NbCS permanence, more “radical” shifts in approach may be required. Collectively, the perspectives presented here could function as a proposal describing the work needed to inform NbCS assessments with the best-available science.

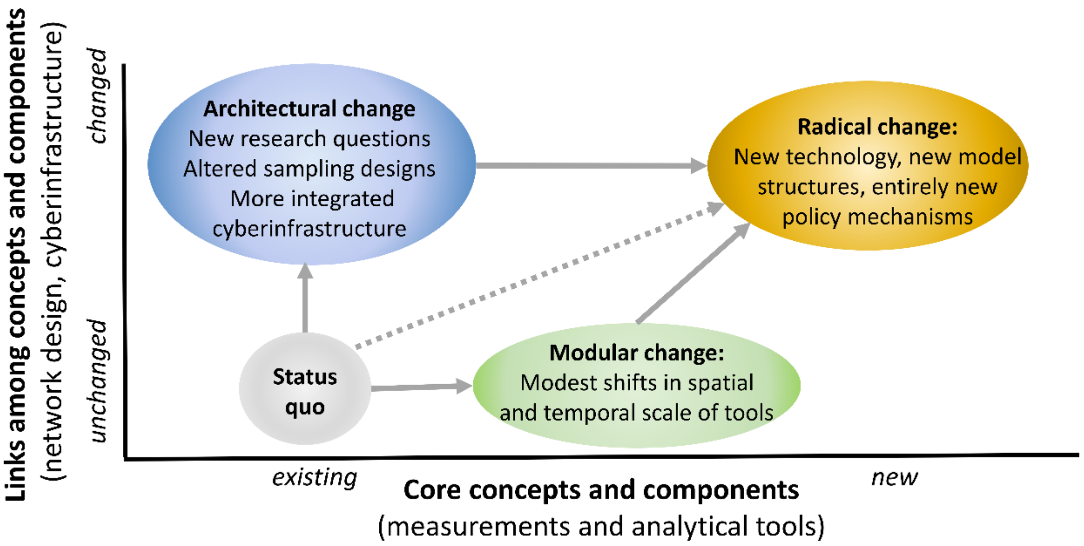


Figure 1: Classes of innovation characterized by changes to the tools themselves (x-axis) or changes to the linkages among the tools (y-axis), modified from Henderson et al. 1990. The bulk of this paper is focused on modular and architectural change, accompanied by some promising directions for "breakthrough" research through radical change.

2. NbCS-relevant data and analytical tools:

The dominant role of terrestrial ecosystems in determining the fate of atmospheric CO$_2$ has been known for decades. Consequently, huge investments of resources have fostered the development of innovative tools for monitoring and quantifying ecosystem carbon cycles (Figure 2). These include tools for quantifying both carbon stocks (or the amount of carbon stored in soil, litter, or plant biomass) and carbon fluxes (which represent the rates at which carbon is transferred into, out of, and within ecosystems). While fluxes can be inferred from the change in stocks over time, this approach only works if all the relevant stocks are measured (which is often infeasible). Moreover, carbon stock data alone are insufficient to reveal the processes responsible for a change in carbon uptake, or to estimate emissions of non-CO$_2$ greenhouse gases like methane and N$_2$O. Right now, the vast majority of the existing approaches for flux measurement and modeling are not being widely applied to NbCS evaluations. Particularly striking is the fact that the only direct observations of land-atmosphere carbon, water, and energy exchanges (from flux towers, Baldocchi et al. 2008) have not yet been systematically assessed for what they can tell us about NbCS impacts (Hemes et al. 2021). Likewise, many next-generation remote sensing products and state-of-the-art process-based models are also not being widely used to inform NbCS policy making or implementation.

A general tradeoff exists between the accessibility of these tools to broad communities of stakeholders, and the robustness with which they describe a full set of relevant ecosystem processes (Figure 3). Biometric soil core and tree survey data are simple, low-cost measurements that are broadly accessible; however, their robustness is limited, as they do not account for all carbon stocks, provide little information about biophysical impacts, and have a low temporal resolution that limits their ability to detect changes quickly. In contrast, flux towers have a high degree of "robustness" linked to their ability to continuously measure the net flux of CO_2 (and other GHGs) between the atmosphere and the ecosystem, as well as a full suite of related water and energy cycle variables. But flux towers are expensive, and quality control and post-processing of flux tower data has historically required specific expertise. Satellites and drones provide spatially robust proxies for NbCS-relevant variables at scales that are increasingly well- matched to farms and fields. However, the temporal resolution of these products is often limited, and no technology yet exists to measure the net flux of CO_2 or other GHGs directly from space.

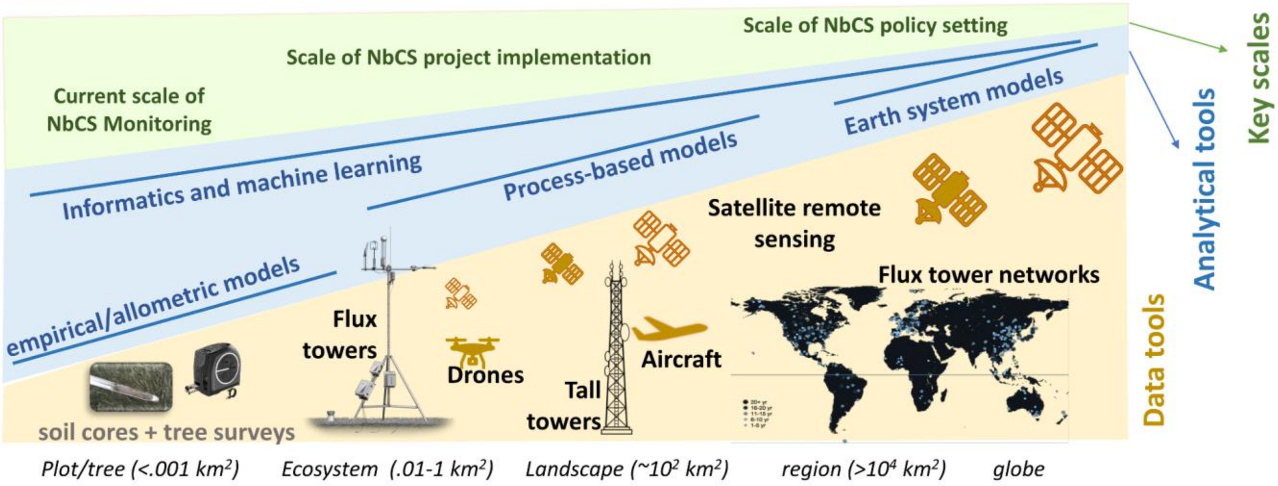


Figure 2: Existing tools and approaches for quantifying carbon pools and GHG emissions from terrestrial ecosystems. See Supplementary Information (S.I.) for detailed description of each tool.

The extent to which data are "open" and discoverable to a wide range of researchers and stakeholders is another dimension of accessibility. Flux tower networks like AmeriFlux, FLUXNET, and NSF's National Ecological Observatory Network (NEON) have long been on the forefront of open data sharing (Baldocchi et al. 2009, Novick et al. 2018, Metzger et al. 2019). Tree inventory data from the USDA Forest Inventory and Analysis (FIA) program (Bechtold & Patterson 2005) are also highly standardized and accessible, and soil carbon data are also becoming more aggregated and open (Arias-Ortiz et al. 2021a, Bond-Lamberty et al. 2020, Malholtra et al. 2019). However, by and large, these networks are not well connected to each other digitally, and with limited physical overlap between network sites that hinders synthesis (Hinckley et al. 2016).

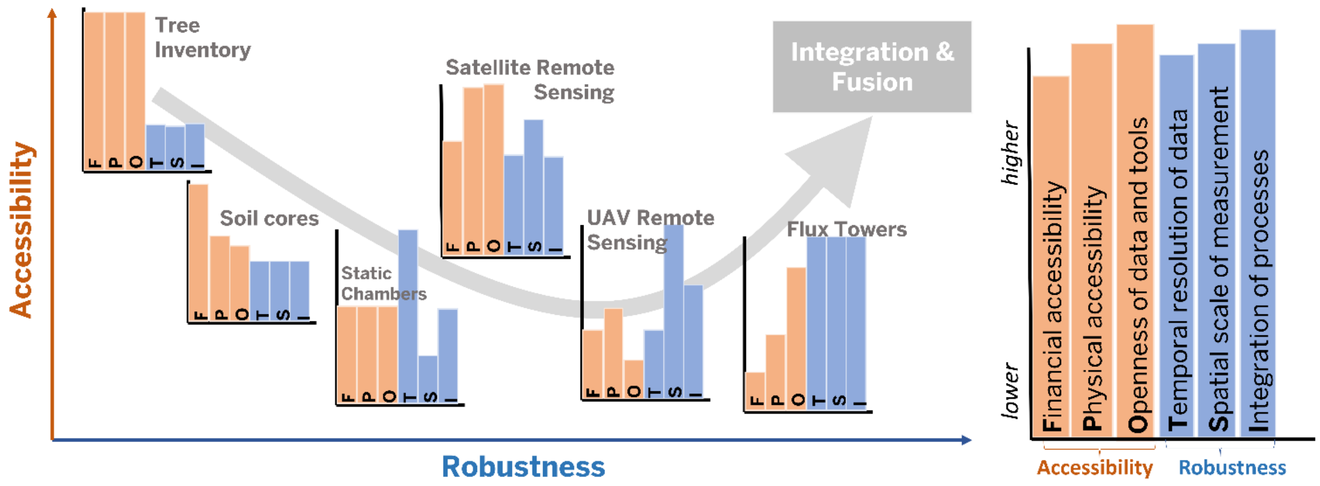


Figure 3: The data tools relevant for NbCS differ along many dimensions of accessibility and robustness. Accessibility dimensions include: ***financial accessibility****, which is inversely related to cost,* ***physical accessibility*** *which describes the ease with which data can be physically obtained, and the* ***openness*** *of the tool, representing the extent to which data and algorithms are findable and usable. Dimensions of robustness include:* ***temporal resolution*** *of the measurements, with more frequent observations enabling faster detection of NbCS impacts and better attribution to mechanisms;* ***spatial scale*** *of the measurements, and specifically the extent to which the measurement is "ecosystem-scale," and biophysical* ***process*** *robustness in terms of whether the approach integrates information on how NbCS may affect not only carbon pools, but also other GHGs and local biophysics.*

In summary, no single approach is a perfect tool for assessing the realizable impacts of NbCS. Thus, throughout the rest of this manuscript, we will emphasize the need for standardized collection of multiple data streams, and outline strategies for fusing these data together to maximize their collective accessibility and robustness while minimizing the unique limitations of each tool.

3: Informing NbCSs with a full set of tools and approaches:

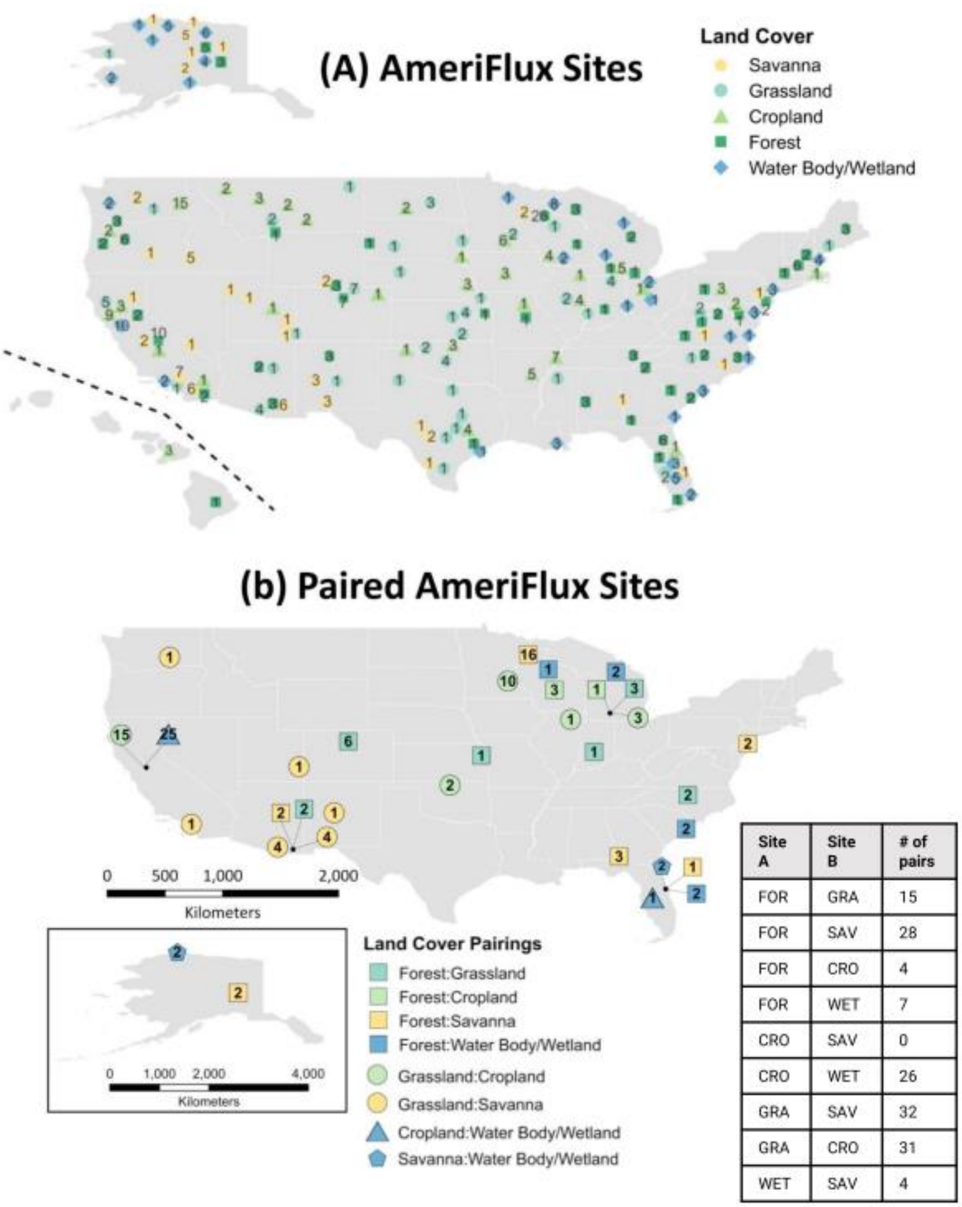
3.1. NbCS assessments at policy-relevant scales: Policymakers and stakeholders need regional- to global-scale assessments of the expected mitigation potential of NbCS, including information about when and where a given approach is most likely to succeed. Ideally, these assessments fulfill the following criteria: 1) they are *informed by* observations of land-atmosphere GHG fluxes *made directly at the ecosystem scale* (~ 1 km^2), thereby integrating over multiple above- and belowground GHG sources and sinks; 2) they are *spatially resolved* (e.g. mapped) and describe *where* the benefits of a given NbCS are greatest; and 3) they are *forward looking*, with careful consideration of the durability of benefits into a future characterized by pervasive climate feedbacks. Right now, a wide gulf separates available information from these idealized criteria. The following subsections highlight ways that flux tower data, survey data, remote sensing data, and models can be used together to narrow the gap. An emergent theme will be the need for "*gold-standard datasets*" to support a wide array of NbCS assessment and validation goals. We imagine these datasets would represent standardized, open and accessible observations of a full suite of carbon stock and flux measurements, from NbCS "treatments" as well as baseline controls, together with information about historic land use. Sustaining long-term flux tower data records should also be a priority, since substantial knowledge gaps remain surrounding the extent to which ecosystem carbon uptake may "saturate" in time (Craig et al. 2021, Curtis & Gough 2018, and see additional text in the S.I.).

3.1.1. Systematic evaluation of ground-based observations:

Forests In forests, which contain a variety of species at different stages of growth, the ability of flux towers to integrate over all carbon sources and sinks is extremely useful. Multi-year time series from

>150 flux towers located in forests are already available from AmeriFlux; of these located in the United States, several dozen represent forests or tree-dominated savannahs co-located with grasslands or croplands (Fig. 4), offering an opportunity for a first-order, ecosystem-scale assessment of the realizable mitigation potential of reforestation as an NbCS. However, the relatively high costs of building and maintaining tall forest towers will always limit their spatial representativeness. In contrast, tree survey data are relatively abundant, thanks to programs like FIA, and may be adequate in some regions to quantify spatial patterns in aboveground biomass (Hemes et al. 2021). However, tree surveys have long (5+ year) sampling intervals, and do not capture patterns of belowground carbon cycling and storage. Comparing tower-based carbon fluxes with estimates derived from biometric survey data from the same site (e.g. Wang et al. 2017, Campioli et al. 2016) can be useful for understanding the biases in carbon uptake potential informed by biometric tree survey data alone. Adding routine biometric sampling (soil cores, tree surveys) to active forest flux tower sites would represent a relatively low-cost initiative that could form the foundation of "gold-standard" datasets for forested NbCS.

Strategic deployment of new forest flux towers may be necessary, especially for NbCS focused on improved forest management, given that we still lack a clear picture for how carbon uptake varies as a function of forest age (Amiro et al. 2010, Law et al. 2003, Novick et al. 2015, Curtis & Gough 2018). Moreover, with some exceptions (Gough et al. 2021), flux towers deployed over forests experiencing similar climate, but different management regimes, are largely absent from the networks. This knowledge gap is important to fill to constrain the potential of improved forest management as an NbCS.



Site A	Site B	# of pairs
FOR	GRA	15
FOR	SAV	28
FOR	CRO	4
FOR	WET	7
CRO	SAV	0
CRO	WET	26
GRA	SAV	32
GRA	CRO	31
WET	SAV	4

Fig. 4: *The spatial distribution of existing AmeriFlux towers in the United States (those that have registered with the network) classified by biome, with numbers indicating the number of towers of each biome type located within ~30 km (Panel a). Panel (b) highlights the location of "paired sites" representing flux towers in different biomes that are within ~30 km. The table describes the number of specific categories of site pairs. Abbreviations are: FOR = forest; GRA = grassland; SAV = savannah; CRO = cropland; WET = wetland or water body.*

Croplands: Because they are already intensely managed, croplands represent relatively “low hanging fruit” for NbCS implementation. Climate mitigation benefits of croplands are largely constrained to soil carbon pools, as the majority of aboveground biomass is removed by harvest. While soil carbon is theoretically easy to measure, creating sampling strategies that adequately capture horizontal and vertical heterogeneity in soil carbon, and its change over time, remains difficult and expensive (Smith et al. 2020). Critically, soil carbon data alone are insufficient to identify responsible mechanisms, such as greater carbon uptake from photosynthesis versus reduced carbon loss in runoff. Concerningly, while soil carbon data tend to report a soil sequestration benefit from cover cropping (Poeplau & Don 2017), at least one study leveraging flux tower data reports that cover crops do not favorably impact net carbon uptake (Baker & Griffis 2005). Moreover, because empirical studies reporting on soil carbon changes are limited for many categories of NbCS, spatially explicit maps of cropland NbCS mitigation potentials do not yet exist. Consequently, we do not know where climate conditions favor or disfavor these strategies.

New pilot flux tower studies that pair an NbCS treatment with a conventionally managed field could bring many insights (Hemes et al. 2021). In theory, flux towers are easier and cheaper to operate in ecosystems with short (<3 m) vegetation, although running them alongside active farm operations and on fast-growing crops can be operationally challenging. Because flux towers cannot detect lateral fluxes out of the measurement footprint, the outflow of dissolved and particulate carbon in runoff should also be monitored, which is relatively easy in the tile-drained systems that characterize much of the Corn Belt. Changes to the leaching of carbon through outflow (Nakhavali et al. 2021) may be an important factor that can cause an increase in soil C that does not necessarily reflect a climate benefit, but rather a tradeoff between GHG emissions in the field and distal emissions downstream. Amending the sampling design around existing cropland flux towers with soil carbon monitoring, outflow monitoring, and static chambers is a relatively straightforward path for creating "gold-standard" datasets for cropland NbCS.

Wetlands and coastal systems: Inundated and/or saline conditions provoke a decline in carbon mineralization and offer an opportunity for enhanced soil storage of carbon. Tidal wetland restoration is an especially promising wetland solution (Kroeger et al., 2017; Fargione et al., 2018), and together with seagrass restoration (or avoided loss), represents significant potential for coastal landscapes (~25 Tg CO_2e yr^{-1}). Away from the coasts, riparian zone and peatland restoration (Vermaat et al. 2021, Gunther et al. 2020a), and methane emissions reduction in rice (Runkle et al., 2018) represent additional opportunities for managed wetlands to contribute to climate solutions. A particular challenge for NbCS is optimizing carbon uptake and sequestration of existing soil carbon against possible production of CH_4 and N_2O (Hemes et al., 2018; Rosentreter et al., 2021; Valach et al., 2021) and biophysical effects (Lee et al., 2021).

Flux towers are well-positioned to assess these impacts, as they enable measurement of complementary gases (CH_4, N_2O) at a high temporal resolution that enables detection and interpretation of spikes (often called "hot moments") of gas release associated with sudden changes in water levels or biological conditions (Turner et al. 2021). They must be placed alongside estimates of lateral carbon flows (Bogard et al. 2020, Arias-Ortiz et al. 2021b) and then analyzed in concert with tidal or water flow data. Like many agricultural sites, the shorter vegetation in these landscapes may reduce some costs, and site management may be conducive to paired or clustered site experimentation. Indeed, more sites are needed to capture the impact of different hydroperiods, vegetation, and biogeochemistry (Matthes et al., 2014); blue carbon flux sites are also only one-third as prevalent as forest, agriculture, or grassland sites (Hemes et al., 2021).

3.1.2: Blending flux tower data with state-of-the-art remote-sensing observations:

Remote sensing data is indispensable for extending ground-based observations to scales relevant for policy making. Already, remotely-sensed proxies for aboveground biomass are being used to map forest carbon stocks (Rodriguez-Viega et al. 2017), and next-generation laser and radar missions (Ustin & Middleton 2021) will produce high-resolution (25 m – 200 m) and three-dimensional biomass estimates of the world's forests. In croplands, remote sensing is already proving useful for detecting the presence/absence of NbCS-relevant management practices like cover crops and no-till management regimes (Azzari et al. 2019, Barnes et al. 2021), as well as crop yield (Guan et al. 2017) - a major carbon cycle "flux." However, while maps of carbon stocks and practice adoption rates provide useful information for NbCS policy evaluation, they are not the same as maps of the potential of a management practice to avoid emissions and enhance sequestration. The change in remotely-sensed biomass over time can be blended with allometric equations to infer the flux of CO_2 from the atmosphere to aboveground vegetation (Rodriguez-Viega et al. 2017, Quegan et al. 2019). But these approaches are generally only possible for forest ecosystems, and they suffer from the same biases affecting biometric tree surveys.

Progress towards spatially explicit maps of NbCS mitigation potential could be enabled by a growing suite of spaceborne instruments, so-called "Flux Towers in the Sky" (Schimel & Schneider 2019), which can sense key aspects of plant function. These next-generation platforms include: a) solar-induced fluorescence (SIF), which is physiologically related to the rate of photosynthesis (Magney et al. 2021), b) column-averaged atmospheric CO_2 which can be used for "inverse" estimates of land carbon fluxes (Wang et al. 2019), and c) instruments for sensing ecosystem water stress (e.g., ECOSTRESS, Fisher et al. 2020, and microwave data on canopy water content, Konings et al. 2021). While the spatial resolution of these satellite products can be coarse, some are now available at scales that match those of individual farms (e.g. ECOSTRESS, Fisher et al. 2020), and the need for finer-scale versions of other products has been clearly articulated (Konings et al. 2021). In many cases, substantial increases in resolution are possible with drone-mounted instruments (e.g. SIF, Mohammed et al. 2019). The information provided by these platforms is sensitive to limitations and biases, which are well-reviewed elsewhere (Konings et al. 20201, Fisher et al. 2020, Magney et al. 2020), and will continue to benefit from validation with flux tower data (e.g. Sun et al. 2017, Fisher et al. 2020), including novel strategies for fusing data across different scales of observation (see Section. 3.3).

Next-generation remote sensing products can also enable machine learning (ML) extrapolation, or upscaling, of flux tower data into gridded maps (Figure 5), with the FLUXCOM project representing the most notable example (Jung et al. 2011, 2019). FLUXCOM is informed by data from flux towers spanning many continents and biomes, and provides an important constraint on global land carbon uptake generally. However, regional discrepancies exist, which can be partially explained by the representativeness of the flux tower data ingested into the ML algorithms (Jung et al. 2019). Several opportunities exist to refine ML methods so they can be used to map NbCS potentials directly for specific regions or biomes. Tower and remote-sensing data for a specific ecosystem type from a specific region (for example, Eastern US temperate forests, or conventionally-managed croplands in the Corn Belt) could be ingested into ML algorithms to produce regional (as opposed to global) ‘baseline’ maps, which could be compared against each other or against data from pilot studies of novel NbCS ‘treatments’. These targeted, regional-scale mapping exercises could also be further guided by ecosystem-scale understanding of the locally important environmental drivers (e.g. Barnes et al 2021).

Cyberinfrastructure that links 'cut-outs' of remote-sensing products with flux tower data at a given site could be an important feature of "gold-standard" NbCS verification datasets.

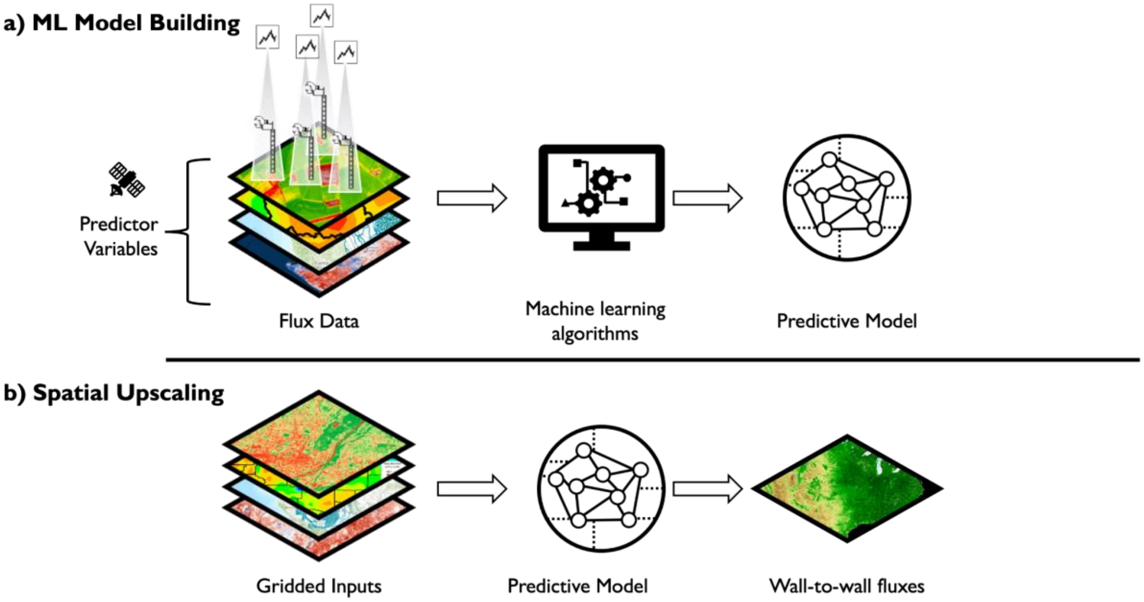


Figure 5. Machine-learning (ML) upscaling of eddy covariance fluxes. a) To upscale fluxes, a ML algorithm first 'learns' relationships between tower fluxes and input variables (i.e. remotely sensed metrics and meteorological data). b) Then, wall-to-wall flux estimates are generated by applying the predictive ML model to each pixel of spatially continuous input variables.

3.1.3 Models. Spatially explicit and forward-facing 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 (e.g. for forest biomass, see Section 3.1.2) and to prescribe the value of project-scale market credits. But the models used for these objectives are highly empirical (e.g. regression based), relying on observed relationships between driver and response variables that cannot be extrapolated into a future characterized by climate conditions profoundly different than those experienced historically.

Earth system models (ESMs), which predict future climate states for a range of anthropogenic emission scenarios, are currently the only tool for mechanistic prediction of climate-ecosystem feedbacks, and the only way to estimate the net effect of the combined physical and biogeochemical impacts into the future. The land component of ESMs -- “Terrestrial biosphere models” (TBMs) -- come in many flavors (Fisher et al. 2018), 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 (see Supplementary Information, hereafter S.I., for an extended discussion).

TBMs have not yet been widely applied to assess NbCS impacts, which may relate to the fact that TBMs were initially developed to transfer fluxes of energy, moisture, and momentum to the atmosphere, with prognostic carbon cycling largely developed in the 2000s (e.g., Cox et al. 2000; Fung et al. 2005). The inclusion of management-relevant processes, including land use change, agriculture, and nutrients, came even more recently (Fisher and Koven 2020). The models are still limited by their capacity to represent management and disturbance processes, and in their skill at quantifying avoided emissions of non-CO_2 GHGs in agriculture. Addressing these limitations is an active research field. For example, mechanistic representation of species demographics and climate-sensitive disturbances like fire are rapidly being implemented in TBMs (Fisher et al. 2018). With respect to agricultural systems, several TBMs now include a basic, but coarse, representation of agricultural and pasture management (Lombardozzi et al. 2020, Pongratz et al. 2018), and TBMs have been used to explore coarse-scale tradeoffs and unintended consequences associated with managed land cover change (Harper et al. 2021, DuVeiller et al. 2020). Thus, despite their limitations, TBMs are very useful for general assessments of when and where NbCS are likely to be most effective (see, for example, Graham et al. 2021, Harper et al. 2018)

However, substantial gaps must be addressed before process-based models can be fully applied to the many pressing sources of NbCS uncertainty, and in particular uncertainties linked to the spatial resolution of the models and their ability to predict the permanence of NbCS benefits. Right now, TBM spatial resolution is typically too coarse to resolve the field and farm scales where carbon credits are assessed and monitored. Moreover, future projections of land carbon uptake are very uncertain in ESMs, particularly into the latter half of the 21st century (Arora et al. 2020). 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 (Friedlingstein et al. 2014). This fundamentally large and potentially irreducible uncertainty (Bonan & Doney 2018) poses major challenges for predicting NbCS permanence. While radical changes to model structure and parameterization may help, several very pertinent questions remain relatively unexplored: First, will the uncertainty problem be reduced when models are tasked with predicting the *change* in land carbon uptake driven by a specific NbCS approach, as opposed to the absolute magnitude thereof? Can this uncertainty be priced into the market systems? And to what extent is model agreement improved when assessed at landscape and regional (as opposed to global) scales? Progress on the latter question may be facilitated by model-data assimilation approaches for near-term “ecological forecasting” (Dietze 2017) and landscape scale model-data fusion (see Section 3.3).

3.2. Towards generalizable frameworks for assessing biophysical co-benefits and/or unintended consequences. Ecosystem carbon uptake is closely coupled with ecosystem water use, such that a managed alteration to land cover designed to affect C cycling will also affect the local hydrology. In general, greater C uptake will likely be associated with greater evapotranspiration (or ET); whether or not this is a favorable biophysical impact depends on climate regime, time of year, and management intent. For example, an increase in ET in spring may be welcomed by farmers throughout much of the Corn Belt, when the primary soil water problem is usually one of overabundance (e.g. flooding, Yin et al. 2020). On the other hand, when and where soil moisture deficits are common, NbCS-driven increases in ET that further deplete soil moisture and runoff may be undesirable. With some exceptions (e.g. Jackson et al. 2005, Windisch et al. 2021), systematic assessments of tradeoffs between NbCS carbon benefits and water cycle consequences are rare, and generally not interpreted in the context of predicted future changes in precipitation and soil moisture balance.

Land cover and management shifts also affect local energy budgets, not only by impacting ET, but also by modifying albedo and sensible heat fluxes. The interplay between these mechanisms can cause NbCS strategies in some regions to cool the surface (e.g. tropical and temperate zone reforestation, Windisch et al. 2021, Zhang et al. 2021, Ge et al. 2019; wetland restoration, Hemes et al. 2018, and conversion to frequently-flooded agriculture lands, Liu et al. 2019). In other cases (e.g. semi-arid and boreal forests), the radiative impacts of NbCS may lead to additional warming (Duman et al. 2021, Lee et al. 2011). Since temperature is rising everywhere, surface cooling relative to the baseline will usually represent a favorable biophysical impact, and some NbCS may represent a tool for local climate adaptation in addition to global climate mitigation. However, several gaps in our understanding of NbCS impacts on local temperature remain, including on the relationship between surface and air temperature (Schwingshackl et al. 2017) and the dynamics of both during climate extremes like heat waves (Tueling et al. 2010).

Substantial opportunity exists to leverage pre-existing data in networks like AmeriFlux for synthetic assessments of carbon and biophysical impacts of NbCS, since they measure most terms of the water and energy cycle. Moreover, unlike carbon uptake, direct quantification of ET and land surface temperature is possible from remotely-sensed data (Fisher et al. 2020), such that more precise mapping of present-day NbCS biophysical impacts should be relatively straightforward, especially when flux tower network data are leveraged for groundtruthing. High-frequency flux tower data could be more carefully analyzed for what they reveal about biophysical impacts at sub-seasonal scales, including hot summer days when cooling benefits are needed most. Finally, emerging approaches that leverage flux tower data to understand land cover change impacts on air temperature (e.g. Novick & Katul 2020, Helbig et al. 2021) can be more widely deployed, noting that near-surface air temperature is arguably the more important target from a climate adaptation perspective.

3.3. Accessible and robust market-relevant quantification of project-scale impacts: Balancing accessibility and robustness is a pivotal challenge facing quantification strategies for NbCS projects, typically implemented at scales <100 km^2. Assessments that forgo direct measurement may enhance accessibility to landowners but run the risk of over- or under-quantifying the true climate benefits, eroding trust in NbCS claims or missing an opportunity to finance important activities (Gunther et al., 2018). The most robust quantification - one that would require frequent physical sampling of each carbon pool over much of the project area - is a Sisyphean task, and will make quantification operationally and economically inaccessible to the vast majority of landowners. The appropriate balance between accessibility and robustness will vary among ecosystem and NbCS project types, scales, policy requirements, and the acceptable level of uncertainty.

In practice, the typical approach to quantifying NbCS benefits relies on periodically inventorying small changes to large carbon stocks, and differencing these from the carbon stocks that would have been present in a baseline case. The latter is usually estimated with empirical models and without consideration of climate feedbacks. For simplicity, most methodologies conservatively omit consideration of less prominent carbon pools when accounting would lead to greater avoided emissions or removals. This status quo approach has the advantage of relying on established tools, but usually omits others (e.g. flux towers) that offer a more robust perspective on the full scope of NbCS impacts (Hemes et al. 2021). The rest of this section discusses approaches for NbCS project evaluation that meet the following criteria: 1) they leverage ecosystem-scale observations for robust yet financially feasible assessments, 2) they rely on transparent and reproducible protocols and algorithms, and objective validation, 3) biophysical impacts and the future permanence of NbCS benefits are accounted for, and 4) they aim to enhance equity and justice for demographic groups who have historically have been, or stand to be, disproportionately impacted by NbCS projects (Fleischman et al. 2020).

3.3.1: Leveraging ecosystem-scale data for monitoring and verification of NbCS projects: Flux towers are attractive tools for monitoring and verifying individual NbCS projects. They provide continuous data on the integrated carbon sources and sinks of an ecosystem, and their high level of precision (~ 50 tC km^{-1}, Hemes et al. 2021) can justify the crediting of a larger fraction of the projected carbon uptake compared to other quantification schemes. Moreover, the rapid response of ecosystem fluxes to land cover and management changes (e,g, Aguilos et al. 2020) can reveal the impacts of an NbCS intervention faster than inventorying slowly-evolving biomass and soil carbon pools.

However, flux towers are expensive to install and operate, and it is not yet clear when they represent a cost-effective tool for project accounting. To address this question, we conducted a sensitivity analysis exploring how the benefit:cost ratio (BCR) of flux tower monitoring varies as a function of the project

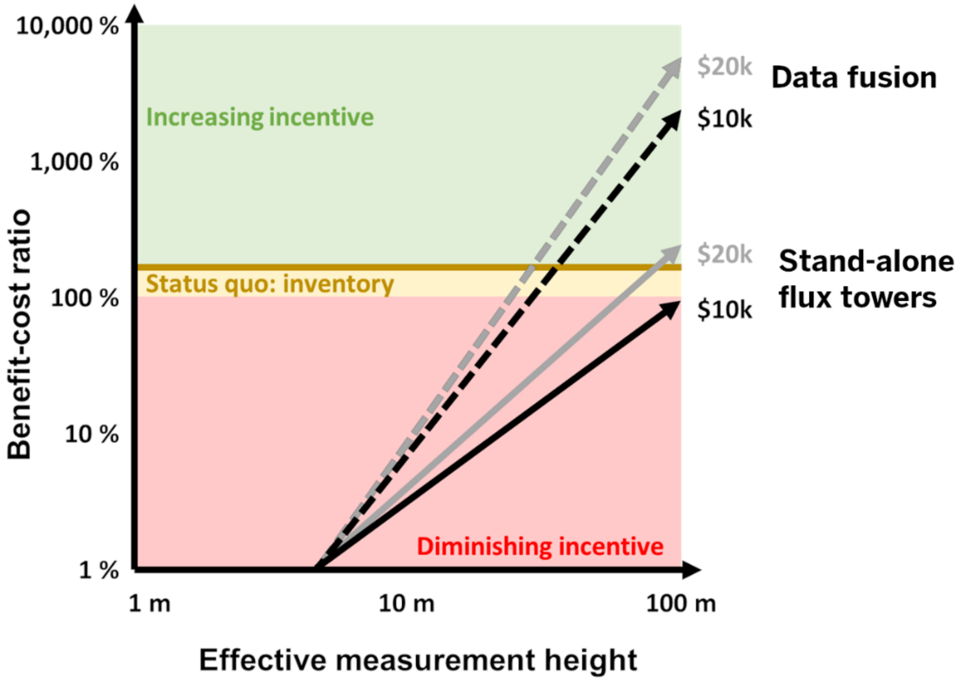


Figure 6: Benefit-cost ratio (BCR) of flux towers, and flux tower data fusion, for NbCS project monitoring. For the conservative constraint of continuously monitoring a 1 km^2 project area, and a 30-year project lifetime, cost neutrality is only approached when using very tall towers. However, substantial gains in BCR are achievable with data-fusion for a virtual extension of the flux tower footprint (see details below). In each case, results are shown for two different estimates of the annual project market value ($10K and $20K per year). The thick yellow line shows the reference BCR of 140%.

market value (representing the combined influence of sequestration potential and price of carbon) and the effective tower measurement height (which determines monitoring cost as well as the size of the measurement footprint, Chu et al. 2021). The analysis adopts the conservative constraint that flux towers should continuously monitor a project area of 1 km^2 (even if that requires the use of multiple towers via an economy of scale) for a project lifetime of 30 years. The project market value was initially set to ~$10,000 km^{-2} yr^{-1}, based on an 'additional' sequestration of 200 tCO2e km^{-2} yr^{-1} and a price of carbon at \$50 per tCO2e, and reference annualized costs representing status-quo monitoring approaches were set to \$7,000 km^{-2} y^{-1} (see S.I. for details). On this basis, the reference BCR was estimated to be ~140%, i.e. the revenue created by the project exceeds its cost by 40%.

While the BCR increased as a function of effective measurement height, even a tall tower (~100 m) did not reach cost-neutrality (BCR = 93%, Fig. 6). BCR also increased as a function of the project market value, but not enough to motivate the use of standalone towers as a monitoring tool in most cases. The cost-effectiveness of flux towers as a monitoring tool may improve if they are deployed for shorter periods of time, or if the monitoring area is reduced to < 1 km^2. More work to understand the minimum requirements for tower time series length and footprint size, with full consideration of uncertainty related to neglected time periods and land surface heterogeneity, should be a research priority.

Substantial opportunity also exists to fuse flux tower data with complementary biometric observations (e.g., Harris et al. 2021; Smith et al. 2020) which can improve the BCR. Specifically, the development of comprehensive physical “Carbon Observing and Data Analysis Systems” (CODAS, see Figure 7) can enable scaling from measurement plots to ecosystems to landscapes with rigor, and also provide information on the processes that flux towers can not see (e.g. lateral runoff, or non-CO_2 GHG emissions that are below instrument detection limits, Detto et al. 2011). In CODAS, data integration and scaling can be achieved with the use of so-called “environmental response functions” (ERFs, Metzger et al. 2013, 2018). The underlying principle of ERF is to use high-frequency (minute to minute) tower footprint variation to extract the relationships between tower-measured fluxes, meteorological forcing variables, and surface ecological and soil properties. Then, these extracted relationships can be combined with remote sensing data to create half-hourly, decameter-resolution carbon flux grids (e.g., Metzger et al., 2013; Xu et al., 2017, Fig. 7), improving accuracy and precision for geographically representative and integrated impact assessments. Importantly, this virtual extension of the tower footprint substantially improves the BCR, such that the status quo BCR can be exceeded for measurement heights on the order of 30 m or greater (Fig. 6) even when carbon prices are relatively low (see S.I. for more details).

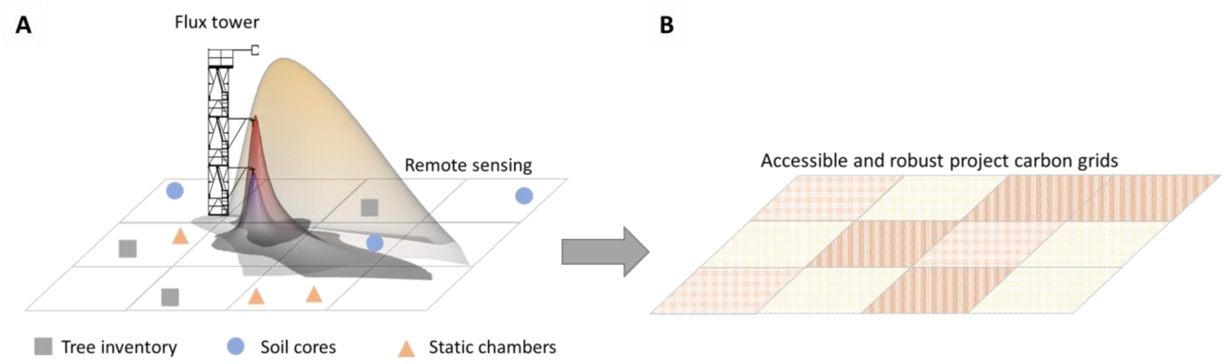


Figure 7: A Carbon Observing and Data Analysis System (CODAS) integrates multi-scale observations to accessible and robust project carbon grids. Panel A: Flux tower CODAS reconciles the differing contexts in space and time among ground-based, airborne and spaceborne carbon observations: data fusion aims to harnesses the benefits and offset the limitations among the individual observation methods, thus fully utilizing their joint information to quantify NbCS project performance. Panel B: The results are project carbon grids at half-hourly and decameter resolution with reduced cost per unit area and improved robustness compared to any individual observation method alone. This near-real time spatialization enables continuous assessment and optimization of localized management practices, and timely intervention for underperforming plots within the NbCS project area.

Novel quantification approaches like ERF data fusion require validation. Here, multi-scale benchmarking approaches originating from earth system modelling can provide a useful path forward. For example, the International Land Model Benchmarking (ILAMB) package (Collier et al., 2018) was originally designed to evaluate and benchmark land model results through comparison with site-, regional-, and global-scale observations, including from airborne CO_2 concentration measurements (Cui et al. JGR-A in press), satellite-based remote sensing (Eldering et al., 2017), machine-learning flux upscaling products (Jung et al. 2019), and carbon cycle models and data assimilation products (e.g., NOAA CarbonTracker, Peters et al., 2007). When referenced to CODAS ground-truthing data, benchmarking systems like ILAMB could provide an important perspective on the magnitude and uncertainty of realized NbCS project benefits, as estimated from a range of ground-, airborne-, and spaceborne observations.

3.3.2: Gold-standard datasets for transparent, reproducible, and objective validation of existing valuation schemes: Right now, most carbon market protocols use a combination of physical data and empirical models for carbon credit valuation, and then rely on independent, third-party verification to ensure methodological standards are met. These verifications tend to be costly, lack standardization and transparency, and do not include truly independent validation based on alternative methods. Multi-scale, integrated, “gold-standard datasets” from representative flux tower sites could be used to validate and improve market verification schemes, especially if they include concurrent observations of carbon stocks, fluxes (from towers and including lateral exports in runoff), and near-surface and satellite remote sensing data. Since carbon accounting seeks to measure CO_2 removals or avoided emissions that are additional to the baseline, gold-standard datasets would be most useful if they: a) capture both pre- and post-intervention periods, b) rely on paired-sites (pairing an NbCS treatment with a baseline control that experiences the same macroclimate), and/or c) are developed in ways that leverage the ERF benefit of localizing fluxes across heterogeneous landscapes.

Substantial physical and cyberinfrastructure is already in place to support the creation of gold-standard datasets. At the time of this writing, data from more than 550 flux towers in the Americas have registered with AmeriFlux, with >400 having shared data. These towers include many paired sites (Fig. 4) and multiple tall towers that are well suited for ERF scaling. Additional site pairs or tall towers could be created with strategic investment in new physical infrastructure; for example, adding a cropland monitoring site near an existing forest tower, or by physical amendments to extend the measurement height of the tower.

Many tower sites are already collecting some combination of biometric data, including measurements of soil C pool size, tree biomass, and/or chamber based emissions (e.g. Wang et al. 2017, Campioli et al. 2016, Hollinger 2021) which themselves may be shared to AmeriFlux to other relevant networks (e.g. the International Soil Carbon Network, Malholtra et al. 2019, or the COSORE soil respiration network, Bond-Lamberty et al. 2020). However, few sites are recording and sharing the full set of observations that would be most useful for robust assessments of NbCS. Moreover, with some exceptions (e.g. NEON sites, Metzger et al. 2019), biometric data are not collected at flux tower sites using standardized protocols. Thus, enhancing at least a subset of existing flux towers with a fuller set of standardized biometric measurements to create open and accessible gold-standard datasets should be a priority moving forward.

The “gold-standard” datasets described here would provide a critical resource for systematic evaluation of existing accounting schemes currently in use in private carbon markets, which vary substantially from one market or entity to the next (see S.I. for details). One way to do this is through model-intercomparison projects (MIPs), which compare predictions from a variety of models driven by the same forcing data. The flux research community has substantial experience performing MIPs to benchmark and cross-compare TBMs (e.g. Huntzinger et al. 2013, Friedlingstein et al. 2020). To our knowledge, no such activity has been attempted for the diverse array of models used to project and quantify NbCS project benefits. A “Carbon Market MIP,” supported by the to gold-standard data, would provide an unprecedented view of when and why the carbon market forecasting schemes differ. It would also enable the exploration of which physiological and ecological processes matter most for the application-based questions at hand (e.g. C storage and permanence), and could directly test the effects of NbCS management actions on these long-term carbon market aims. These information-rich datasets would also permit a systematic “measurement intercomparison” project, to understand where and why empirical accounting approaches differ. Prior work comparing flux tower and biometric data has been limited to forests (Wang et al. 2018, Campioli et al. 2016), and not designed with the specific goal of evaluating quantification schemes actually used in carbon market systems. Finally, these open and accessible datasets could also be accessible to private entities (e.g. independent 3rd party verifiers) working to develop new approaches for market-ready accounting protocols.

3.3.3: Biophysical impacts and permanence: NbCS projects that modify local water and energy cycles in ways that exacerbate the negative consequences of climate change are counterproductive. On the other hand, NbCS projects that confer adaptative benefits for local hydrology and temperature may be more “valuable” from a climate mitigation and adaptation perspective. However, strategies to incorporate biophysical impacts and other co-benefits in carbon market structures are not at all clear (Anderson et al. 2011), since biophysical impacts tend to be local or regional, whereas enhanced C uptake or reduced GHG emissions are global benefits. It is also counterproductive to offset CO_2 emissions with carbon stored in forests that are likely to be decimated by wildfires, drought, or insect outbreaks within a few decades. Viable paths for factoring permanence into carbon credit valuation are also murky: the simple empirical models used for project accounting do not have a mechanism for considering climate feedbacks, whereas highly mechanistic Earth System Models do not agree on how climate feedbacks will impact global land carbon uptake. Rigorous, multi-method approaches to estimating permanence risks - even if uncertainty is high - are urgently needed.

For these reasons, incorporating biophysical feedbacks and permanence into market valuation schemes would likely require radical transformation of accounting and verification protocols, data, and model structures. In the case of biophysical impacts on energy balance, it may be relatively straightforward to "put a price" on the local temperature impacts of an NbCS strategy, since changes in both carbon and energy balance fluxes can be expressed in units of "radiative forcing" (Williams et al. 2021) or CO_2-e (Windisch et al. 2011). Moreover, if robust projections of carbon storage permanence and associated uncertainty become possible at the project scale, market structures should be able to accommodate some discounting of credits, since protocols already accommodate contributions to "buffer" insurance pools.

However, these new market structures would certainly take time to implement. In the meantime, policy mechanisms could be developed that specifically favor the implementation of NbCS in places where biophysical impacts are likely to be favorable, and where the threat of impermanence is comparatively low. For example, in the mesic and highly productive Eastern US, the risks of wildfire, drought, and insect-driven tree mortality are relatively small (Anderegg et al. 2021), and enhancing plant cover in the Eastern part of the country tends to have a surface cooling effect (Zhang et al. 2020, Kaye & Quemada

2017). Thus, NbCS projects in the Eastern US that enhance tree cover may be a “safer bet” when compared to projects in the drought- and fire-prone Western US or Alaska.

3.3.4 Inclusivity of solutions: Developing nations, poorer communities, and black, indigenous, and other people of color (BIPOC) communities frequently bear the brunt of climate change impacts (Hardy et al. 2017, Hoffman et al. 2020), while more developed nations and privileged communities often disproportionately benefit from greater monetization of NbCS and associated research funding (Lamb et al. 2019). Yet, many indigenous regions across the globe manage large carbon stocks, especially in aboveground biomass (Walker et al. 2014), which makes these regions especially vulnerable to climate change (Ramos-Castillo et al. 2017). In addition, continuous discrimination and underrepresentation of historically minoritized groups is especially prevalent among geoscience research communities (Ali et al. 2021, Marin-Spiotta et al. 2020). These problems require structural changes within academia, starting with inclusive mentoring and fieldwork policies, cultural exchanges, more funding opportunities for BIPOC students and researchers, and changes in the focus of teaching (Ali et al. 2021).

NbCS activities funded via emission offsets must be structured in a way that does not delay meaningful decarbonization, most especially in industries whose co-pollutants inordinately impact historically disadvantaged communities. Moreover, inclusive and equitable practices for NbCS monitoring and implementation will require: early and transparent engagement with stakeholders, incorporation of traditional knowledge and cultural values, explicit mechanisms for stakeholder self-determination, as well as continuous cross-cultural education and training of principal investigators (Ramos-Castillo et al. 2017, Reo et al. 2017, Thompson et al. 2020, Varghese et al. 2021). For example, in ecosystem service markets, large emphasis has been placed on monetizing the material contributions of ecosystems to human wellbeing (Van Riper et al. 2017). However, for Indigenous communities, these outcomes often do not meet their objectives, highlighting the need to include social benefits and values to NbCS solutions (Olander et al. 2018). NbCS projects should also ensure the rights to land ownership, as well as full transparency of accounting methods to establish accessible, scientifically sound, and sustainable market options to prevent exploitation of historically underrepresented communities.

Moreover, sustainable and equitable carbon markets require a holistic picture of the co-benefits and unintended consequences of NbCS (Seddon et al. 2020), including the biophysical impacts to local water and temperature regimes. Flux towers provide information on these impacts, and when installed for long-term deployment, towers may also offer communities with opportunities for early detection of natural disturbances, such as drought or elevated fire risk. Collectively, flux tower networks have the infrastructure and resources to contribute to building stronger communities through collaborations, outreach, and support for members from a diverse set of backgrounds; however, they remain strongly dominated by towers and personnel from the Global North. Broadening the geographic and demographic composition of the networks should be a clear organizational priority moving forward.

4. Summary and Conclusions: The scientific community certainly has not reached consensus on the realizable climate benefits of Nature-based Climate Solutions (Fleischman et al. 2020, Anderegg et al. 2020, Seddon et al. 2020). Nonetheless, the surprising enthusiasm for NbCS, coming from an unusual set of public and private entities, will likely make NbCS strategies a core component of U.S. climate mitigation policy moving forward. It is imperative that these policies be crafted and implemented with the best-available science. In this paper, we propose multiple strategies for a modular and structural shifts in research foci that will allow us to confront the most pressing sources of NbCS uncertainty, at both the project scale and at the regional scales where policy decisions are made. These include:

- Synthesize existing flux tower network data for: a) direct assessment of mitigation potential and associate biophysical impacts in paired flux tower sites, b) creating regional NbCS mitigation and adaptation potential maps through machine-learning upscaling and/or benchmarking of next generation remote-sensing products, and c) answering basic questions about how much flux tower data is necessary to improve the precision and cost effectiveness of project-scale monitoring and verification.

- Strategic deployment of new flux towers in underrepresented biomes (e.g. intermediate age forests, ecosystems managed with understudied NbCS strategies) and to increase the number of paired sites in the network.

- The creation of “gold-standard” datasets for a representative set of sites, featuring concurrent observations of carbon stocks (e.g. soil and tree inventories), fluxes (from towers and including lateral exports in runoff), and near-surface and satellite remote sensing data. These datasets could: a) reveal biases between the biometric data typically used in NbCS assessments, and the relatively more robust information contained in flux tower and some remote sensing data streams, b) function as a platform for a carbon market model intercomparison project, and c) function as a testbed for novel schemes to quantify and monitor NbCS impacts.

- Operationalizing flux tower data fusion approaches (ERF, CODAS) that a) facilitate co-interpretable gold-standard datasets that reconcile the differing space- and time scales among biometric, flux tower, and remote sensing observations, b) virtually extend the flux tower footprint for robust NbCS project monitoring with favorable benefit:cost ratios, and c) reliably nest in-situ information into the communication among remote sensing, models and tools across project- and policy-relevant scales.

- Building more demographically diverse and representative research communities that are better equipped to develop equitable solutions for NbCS implementation.

We also recognize that some sources of NbCS uncertainty are more complex, and belie the expectation that they can be confronted with “modular” or “architectural shifts” to research infrastructure (Figure 1). These include the extraordinarily complex challenge of predicting how climate feedbacks will affect future land carbon uptake, as well as the difficult question of how to value biophysical impacts in carbon market structures. These knowledge gaps may require radical changes in our data and analysis tools, and/or radical shifts in how private carbon markets are structured. In the meantime, we emphasize the need for at least first-order predictions about where NbCS biophysical impacts and permanence are likely to be most favorable.

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