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An Ecosystem-Scale Flux Measurement Strategy to Assess Natural Climate Solutions

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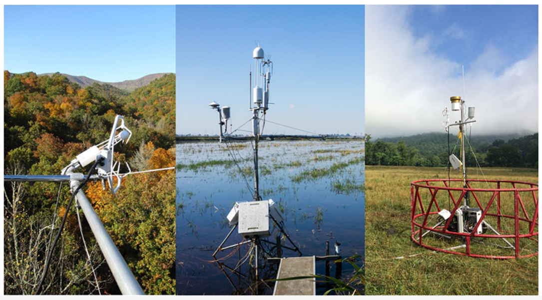
ABSTRACT: Eddy covariance measurement systems provide direct observation of the exchange of greenhouse gases between ecosystems and the atmosphere, but have only occasionally been intentionally applied to quantify the carbon dynamics associated with specific climate mitigation strategies. Natural climate solutions (NCS) harness the photosynthetic power of ecosystems to avoid emissions and remove atmospheric carbon dioxide (CO_2), sequestering it in biological carbon pools. In this perspective, we aim to determine *which* kinds of NCS strategies are most suitable for ecosystem-scale flux measurements and *how* these measurements should be deployed for diverse NCS scales and goals. We find that ecosystem-scale flux measurements bring unique value when assessing NCS strategies characterized by inaccessible and hard-to-observe carbon pool changes, important non-CO_2 greenhouse gas fluxes, the potential for biophysical impacts, or dynamic successional changes. We propose three deployment types for ecosystem-scale flux measurements at various NCS scales to constrain wide uncertainties and chart a workable path forward: "pilot", "upscale", and "monitor". Together, the integration of ecosystem-scale flux measurements by the NCS community and the prioritization of NCS measurements by the flux community, have the potential to improve accounting in ways that capture the net impacts, unintended feedbacks, and on-the-ground specifics of a wide range of emerging NCS strategies.

How should ecosystem-scale flux measurements be deployed for Natural Climate Solutions?



1. INTRODUCTION

Stabilizing global temperature at 1.5 °C will require, in addition to rapid decarbonization, significant removal of carbon dioxide (CO_2) from the atmosphere.[1] This goal can be achieved through a combination of engineered and biological CO_2 removal strategies.[2] Earth's land surface currently removes more than a quarter of anthropogenic carbon emissions through biological processes.[3] Intentionally managing ecosystems for additional climate mitigation is a critical component of many climate stabilization pathways. Despite their prominence in international and subnational climate change agreements and policy proposals,[4,5] and a recent flurry of public and private investment,[6] there is an incomplete understanding of the climate impacts and trade-offs inherent in biological climate mitigation activities.[7,8]

Natural climate solutions (NCS) provide climate benefits through two broad pathways: avoiding greenhouse gas (GHG) emissions that would otherwise occur from ecosystems, or removing CO_2 from the atmosphere through photosynthesis and sequestering it in biological carbon pools[9,10] (Figure 1). The majority of IPCC emission pathways consistent with keeping global temperatures below 2 °C rely on biological CO_2 removal practices,[11] even though many of them are unproven at scale.[12,13] Compared to other more "engineered" CO_2 removal technologies that rely on capture (biological or direct air) and injection of CO_2 into geological reservoirs,[12] NCS are considered to be low cost,[2] immediately ready for large-scale deployment,[14] and not reliant on substantial energy inputs.[15] They are also generally assumed to achieve environmental and social cobenefits, although ecological and social trade-offs will need attention as NCS projects scale.[16−18]

Despite these high expectations, there are gaps in our understanding of where, when, and how NCS strategies will be effective components of a climate-solutions portfolio, especially given the urgency with which activities must scale from current levels (much less than 1 Gt CO_2e) to the 10s or hundreds of gigatons necessary for meaningful negative emissions.[16,19] For

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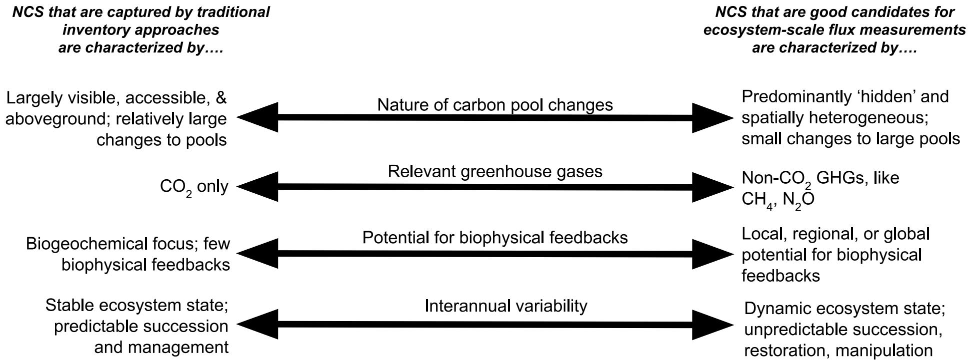

Figure 1. We propose four criteria to guide decision making about where and how eddy covariance can be of most value for assessing emerging NCS strategies.

Table 1. A Significant Portion of the Global Mitigation Potential for Natural Climate Solutions Could Come from Strategies with Hidden or Inaccessible Carbon Pool Changes, Non-CO_2 GHGs, the Potential for Biophysical Feedbacks, and Interannual Variability and/or Succession[a]

Ecosystem Type	Strategy	Mitigation typology	Global mitigation potential 95% CI (Pg CO_2e / yr)	Nature of predominant carbon pool changes	Relevant greenhouse gases	Potential scale of biophysical feedbacks	Level of interanual variability or succession
Forest	Reforestation	enhanced sequestration	2.73-17.87	soil, woody biomass	CO_2	Global	High
	Avoided Forest Conversion	avoided emissions	3.00-4.21	soil, woody biomass	CO_2	Global	Low
	Natural Forest Management	enhanced sequestration	0.92-8.22	woody biomass	CO_2	Regional	Medium
	Improved Plantations	enhanced sequestration	0.17-1.01	woody biomass	CO_2	Regional	Medium
	Avoided Woodfuel	avoided emissions	0.33-0.41	woody biomass	CO_2	Local	Low
	Fire Management	avoided emissions	0.17-0.41	woody biomass	CO_2	Local	Medium
Wetland	Coastal Wetland Restoration	enhanced sequestration	0.62-1.06	soil, herbaceous biomass	CO_2, CH_4, N_2O	Local	High
	Peatland Restoration	enhanced sequestration	0.71-2.47	soil, herbaceous biomass	CO_2, CH_4, N_2O	Regional	High
	Avoided Peatland Impacts	avoided emissions	0.24-1.21	soil, herbaceous biomass	CO_2, CH_4, N_2O	Regional	Low
	Avoided Coastal Wetland Impacts	avoided emissions	0.14-0.47	soil, herbaceous biomass	CO_2, CH_4, N_2O	Local	Low
Agriculture & Grassland	Biochar Application	enhanced sequestration	0.64-1.46	soil	CO_2	Regional	Low
	Trees in Croplands	enhanced sequestration	0.47-1.86	soil, woody biomass	CO_2	Regional	Medium
	Cropland Nutrient Management	avoided emissions	0.40-0.96	soil, herbaceous biomass	N_2O	Local	Low
	Grazing: Improved Feed, Animal Management, Optimal Intensity, Legumes in Pastures	avoided emissions	0.27-3.43	soil, herbaceous biomass	CO_2, CH_4, N_2O	Local	Low
	Conservation Agriculture	enhanced sequestration	0.31-0.52	soil, herbaceous biomass	CO_2	Local	Low
	Improved Rice Cultivation	avoided emissions	0.28-0.32	soil, herbaceous biomass	CH_4, N_2O	Local	Low
	Avoided Grassland Conversion	avoided emissions	0.08-0.37	soil, herbaceous biomass	CO_2	Regional	Medium

[a] Global mitigation potential 95% confidence intervals from ref 9.

many types of NCS,[9,20,21] traditional carbon inventory approaches are incomplete or impractical. These traditional approaches periodically measure the C stocks in biomass[22] or soil,[23] in an effort to quantify relatively small changes associated with an NCS activity. They can be labor intensive, typically only focus on CO_2, may miss important carbon pools, and have low spatial and temporal representativeness. In many cases, current accounting relies on incomplete, or outdated data.[24] A significant portion of the global potential (Table 1) for NCS could come from ecosystem modifications that require a more sophisticated understanding of the changes in multiple ecosystem carbon pools and thus require a different set of tools (Figure 1).

Fortunately, eddy covariance measurement systems, deployed on what are known as flux towers, allow for the most direct observation of the net exchange—or flux—between ecosystems and the atmosphere at a management-relevant scale.[25] By integrating carbon pool changes from the soil to the canopy, these data represent the combined atmospheric sources and sinks of GHG, water, and energy exchange. Organized into global and regional open-source data-sharing networks,[26−28] eddy covariance flux data could play an expanded role in disentangling the benefits and trade-offs associated with NCS implementation.

Ecosystem-scale flux measurement systems provide unique opportunities to evaluate the performance of NCS. First, sensors on flux towers make observations continuously, allowing for integration of annual, multiyear or even decadal records of land-atmosphere exchange when combined with statistical gap filling methods. The technique thus captures variability over seasonal and diurnal cycles, as well as the influence of interannual climate variability, management, and disturbance events. Second, unlike most other approaches for directly measuring GHG fluxes, eddy covariance is non-invasive; it does not introduce artifacts on ecosystems during measurements that are potentially induced by chamber, cuvette, soil cores, or destructive biomass sampling. Third, eddy covariance is spatially integrative over ecologically meaningful scales, capturing the myriad biotic and abiotic processes conspiring to exchange mass and momentum with the atmosphere. Its measurement footprint (typically 100−1000 ha, depending on tower height and wind dynamics)[29] gives eddy covariance the power to provide data for a reasonably sized management unit in real time, aggregating across multiple fast and slow, apparent and hidden, above-ground and belowground carbon pathways.

To date, ecosystem-scale flux measurements have been used primarily to gain a richer process-based understanding of how ecosystems work.[30] Despite serving as a "gold-standard" for estimates of land-atmosphere carbon exchange,[31,32] eddy covariance flux measurement systems have only occasionally been intentionally applied to quantify the mitigation potential of emerging NCS strategies (e.g., refs 33−35), to scale regional NCS portfolio performance, or to monitor compliance or voluntary carbon sequestration projects (e.g., refs 36 and 37).

In this perspective, we examine the role that ecosystem-scale flux measurements could play in evaluating, prioritizing, and implementing NCS. We synthesize into four criteria the characteristics of NCS strategies for which ecosystem-scale flux measurements, as opposed to traditional inventory techniques, add particular value (Section 2). Next, we develop a framework for how ecosystem-scale flux measurements should be deployed for diverse NCS scales and goals (Section 3) before offering some concluding thoughts (Section 4). Together, we see great potential to catalyze mutually beneficial solution-based collaborations between the flux and the NCS communities.

2. SUITABILITY OF ECOSYSTEM-SCALE FLUX MEASUREMENTS FOR NATURAL CLIMATE SOLUTIONS

Nature of Carbon Pool Changes. While many conventional carbon inventories consider changes to only one or a few dominant pools of carbon,[22] ecosystem-scale flux measurements have the ability to simultaneously measure changes in multiple pools. This insight derives from eddy covariance's direct measurement of net ecosystem exchange (NEE), the difference between gross photosynthetic uptake and ecosystem respiration.

Many emerging NCS strategies involve changes to "hidden" and spatially heterogeneous carbon pools (e.g., soil), important above and belowground pools (e.g., perennial grasslands), hard to access biomass (e.g., in mangroves), or saturated sediments (e.g., in peatlands). These kinds of NCS ecosystems that are not dominated by aboveground woody biomass encompass between a quarter and a third of the global NCS potential (Table 1, based on ref 9) but present challenges for traditional inventory approaches. Flux tower measurements can be particularly useful because they integrate over multiple carbon sources and sinks and can resolve relatively small changes in carbon pools that would otherwise require extensive and expensive sampling regimes. To characterize how suitable flux measurements are for a specific NCS activity, it is important to consider visibility (to satellites and airborne sensors), access (to on-the-ground allometric biomass techniques), spatial heterogeneity, detection limit (relative magnitude of changes to the carbon pool), and location (aboveground, litter, belowground, saturated) of the predominant pool changes.

Forest-NCS strategies like natural forest management or reforestation, which primarily promote changes in above-ground, long-lived woody carbon pools, make up the majority of the global NCS potential (Table 1, based on ref 9). These strategies may be most commensurate with traditional carbon inventory approaches (Figure 1, left side). Extensive biometric measurements have been compared to eddy covariance measurements, yielding short-term disagreements, due to lags between photosynthesis and tree growth, but multiyear agreement.[38,39] (These biometric comparisons quantify changes in carbon pools that are not always considered in project-based carbon accounting of forest NCS, like soil, detritus, and fine root litter.[22]) Even in forest-NCS, though, valuation of ecosystem services beyond carbon removal may warrant application of ecosystem-scale flux measurements.

Relevant Greenhouse Gases. NCS are typically designed to preserve or increase carbon stocks, but these ecosystem modifications also have the potential to alter emissions of other important GHGs, especially nitrous oxide (N_2O) and methane (CH_4). NCS estimates often fail to sufficiently account for non-CO_2 trace gases that could enhance or degrade the net climate impact.[40,41] Eddy covariance's ability to measure all of the major trace gases exchanged by ecosystems make it a powerful option for understanding the entire GHG budget both for NCS strategies that intentionally modify CH_4 and N_2O regimes and for those that may unintentionally impact net fluxes.

In wetland restoration projects, for example, increased CH_4 emissions can be an unintended consequence of the ecosystem modification[40] and can change the magnitude or the sign of the net climate impact. Nitrous oxide, another potent trace gas that can be measured by eddy covariance,[42,43] is highly intermittent. In saturated, disturbed, and high-nutrient systems a substantial fraction of the annual flux may occur in short bursts or in particular "hotspots",[44] which eddy covariance can uniquely quantify. In fact, there is evidence that much of soil C sequestration benefits could be offset by increased N_2O emissions,[41,45] emphasizing the need for understanding the multi-GHG dynamics of NCS. Several NCS, especially in agricultural ecosystems, are explicitly designed to reduce emissions of CH_4 and N_2O (Table 1). Ensuring that these activities, like water table manipulation to reduce CH_4 emissions from rice cultivation,[35] do not come at the expense of CO_2 or N_2O is essential to a complete understanding of the multi-GHG trade-offs.

Table 2. Practical Deployment of Ecosystem-Scale Flux Measurements for NCS Can Be Grouped into Three Use-Cases

use-case	goal	metric	implementor	scale	funding
pilot	collect specific, high quality data to help prioritize and quantify the impact of specific NCS strategies	local to regional practice-specific emission reduction potentials that relate NCS activity to fluxes	academic institutions, foundations, government agencies	site-level or meso-network observations contrasting land use/management, or space-for-time treatments	research funding to establish constraints and identify potential unintended feedbacks
upscale	facilitate spatially extensive measurements of NCS performance across broad geographies	scaling functions that relate spatially extensive, gridded inputs, to observed NCS fluxes	academic institutions, government agencies at multiple jurisdictional scales	regional to jurisdictional, based on regional potential and uncertainty in NCS portfolios. Multiple sites needed for upscaling.	quality-control investments for scaling and validating a regional NCS portfolio or compliance system
monitor	quantify the climatic performance of a specific compliance NCS project	annual net carbon and GHG balance of NCS project area	project implementor, project aggregator, land owner	project-scale, based on carbon and ecosystem stratification within project, and requirements of quantification methodology	compliance requirements or market-based incentives

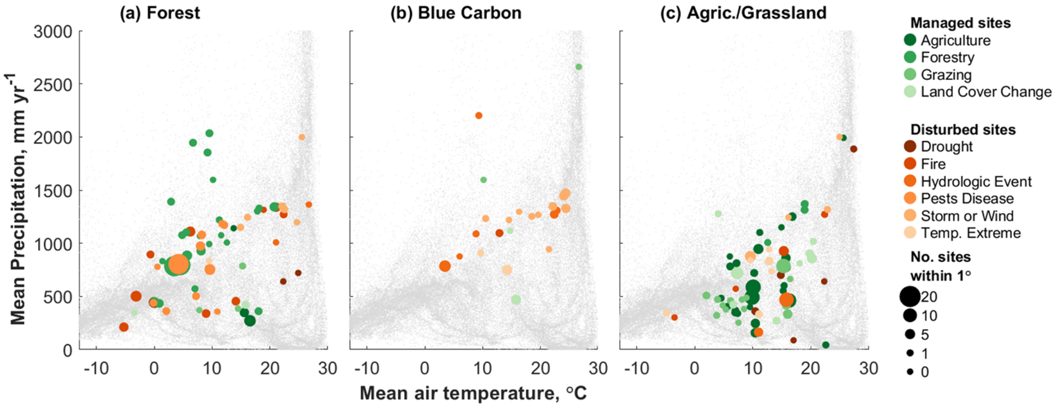

Figure 2. Ameriflux sites that report being managed (green colors) or disturbed (orange colors) have proliferated over the past decade, allowing potential for paired experimental designs that can provide insights into NCS performance. Sites are grouped by NCS ecosystem "type" (a−c), sized by number of sites (disturbed, managed, or "natural") within 1 degree. Gray background points represent the climate envelope of Earth, with each point representing the mean climatic conditions of a 0.5° pixel.[84] There are 94, 31, and 130 "managed" or "disturbed" sites in each category (forest, blue carbon, agriculture/grassland) out of 494 total Ameriflux sites. Ameriflux site data from https://ameriflux.lbl.gov/.

Potential for Biophysical Feedbacks. NCS are designed to permanently reduce the amount of globally well-mixed GHGs in the atmosphere, but they also lead to biophysical impacts, including changes in albedo, energy partitioning, and surface roughness. These biophysical changes, usually local to regional, but potentially global in scale (Table 1), can enhance or degrade the overall climate benefit of a particular NCS activity or portfolio[46−49] and strongly impact ecosystems and human communities within and in proximity to NCS landscapes. Eddy covariance and its associated instrumentation are able to measure these types of impacts, such as changes in surface and radiative temperature,[50,51] water use,[52,53] and reflectance.[54]

The biophysical feedbacks associated with afforestation and reforestation[46,48,55] and some cropland management approaches[56−58] are reasonably well-observed, while feedbacks associated with novel NCS strategies, like wetland restoration,[59,60] are less well characterized. In some situations, like reforestation in the temperate or tropical zones, associated biophysical surface cooling enhances the overall climate mitigation potential. In others, NCS activities may alter the energy balance to cause local warming.[61] We currently lack accounting mechanisms sophisticated enough to quantitatively weigh the biophysical impacts of NCS activities against the biogeochemical,[62] or to integrate biophysical effects into a climate mitigation portfolio. Without accounting for these unintended side effects, as is possible with ecosystem-scale flux measurements, we risk scaling up NCS strategies that are self-defeating or detrimental.

Interannual Variability. While many NCS estimates assume steady-state conditions,[10,63] a long-term perspective of the potential of NCS strategies must contend with the nonstationary nature of carbon uptake over time scales of years to decades.[64−67] Even in seemingly undisturbed or unmanaged ecosystems, long-term trends in carbon uptake can result from exogenous factors like CO_2 fertilization, nitrogen deposition, and increased prevalence of weather extremes.[68,69] To count on NCS strategies to provide long-term carbon removal requires a sophisticated understanding of how NCS ecosystems take up and release carbon at various time scales, which has long been a core focus for the eddy covariance community.[27]

Because flux tower data are not autocorrelated beyond a period of days to weeks,[70] it is possible to observe how ecosystem processes respond to both short- and long-term environmental changes.[71] This allows us not only to quantify net reductions in ecosystem fluxes due to disturbance, management, and succession in real-time, but also to gain insight about the mechanisms by which these processes impact gross ecosystem fluxes.[72−75] These kinds of ecosystem-scale flux data can help train models and remote sensing products to integrate permanence risks to NCS at a spatially extensive scale.

Sets of eddy covariance towers (meso-networks) deployed within a space-for-time experimental design have been used to understand the carbon dynamics of postdisturbance succession without having to wait many years for succession to play out at a single site.[76,77] Constraining carbon recovery trajectories, like in abandoned agricultural land restoring to forests in the southeastern U.S.[51] or irrecoverable carbon hotspots[78] like peatlands and other blue carbon ecosystems,[33] are critical jobs for ecosystem-scale gas exchange measurements.

3. DEPLOYMENT OF ECOSYSTEM-SCALE FLUX MEASUREMENTS FOR NCS

Deployment of ecosystem-scale flux measurements for NCS could fall into one of three (nonmutually exclusive) use-cases: "pilot", "upscale", and "monitor". The first leverages eddy covariance in a research context to pilot novel NCS and collect specific, high quality data on constraints and trade-offs that help prioritize, lay the groundwork for, and quantify the potential for larger-scale implementation. The second use-case focuses on targeted deployment of eddy covariance as an anchor measurement that could be used to upscale and validate remotely sensed observations across regions or jurisdictions. The third relies on eddy covariance for ecosystem monitoring, validating a putative carbon credit or supporting compliance with an emissions reduction mandate (Table 2).

Piloting Novel NCS. Site or meso-network measurement of the ecosystem-scale fluxes of NCS can offer critical insights into their performance, trade-offs, and unintended impacts. We lack sufficient direct observations of the net climatic impact of many novel NCS practices, and in much of the world's climate space (Figure 2). Research-driven "pilot" deployments can capture high quality new data about the performance of a particular NCS, under a specific management practice. The community should work toward incentivizing pilot deployments of promising NCS practices in new climate space (Figure 2), much of this being in the tropics.[79] Even so, there is already great potential within the existing Ameriflux database—including 1160, 221, and 741 site-years of fluxes across three major categories of NCS ecosystems (forest, blue carbon, and agriculture/grassland). These, in addition to future deployments, will help quantify complete, practice-specific, emission reduction potentials to guide prioritization of where and how NCS should be rolled out most efficiently and effectively.

Eddy covariance's direct measurement of NEE allows for observation of a broader set of pool changes and fluxes across an NCS ecosystem. The climatic footprint of some NCS strategies, however, extend beyond the ecosystem boundary. For this reason, pilot eddy covariance deployment should be combined with complementary measurements to capture the complete net ecosystem carbon balance: the sum of NEE and carbon compounds that advect, drain, deposit, diffuse, leach, or are physically transported into or out of the ecosystem.[80] For example, measuring lateral transfer of dissolved carbon helps close a restored wetland's mass balance;[81] agricultural NCS projects must closely measure the carbon removed in harvest.[82] When substantial GHG impact occurs outside of the immediate system boundary of the NCS practice, these emissions must be quantified through alternate means and integrated with flux measurements for complete life-cycle accounting.

Pilot eddy covariance deployment for NCS may utilize experimental techniques like space-for-time chronosequences (e.g., ref 33), paired control-treatments (e.g., ref 35) that may include ecosystem manipulation (e.g., ref 83), environmental gradients (e.g., ref 50) or even "natural" experiments to critically test the potential of a specific NCS strategy compared to business-as-usual. Sites that experience diverse management practices and disturbance events within relatively close proximity of neighboring sites (Figure 2) could allow for paired treatment-control comparisons.

Upscaling to Regional Portfolios of NCS. Eddy covariance deployments can serve as the anchors to establish credible scaling functions and validate remotely sensed observations across the vast land areas that NCS deployment may require.[21] This type of upscaling yields an affordable and efficient way to monitor widespread NCS strategies using model-measurement hybrids that require relatively few, typically remotely sensed inputs. In this way, networks of individual pilot deployments can be leveraged to provide information at the jurisdictional or regional scale.

Deployment of eddy covariance networks in tandem with high resolution remote sensing methods—near-surface, airborne, and satellite—facilitates quantification of landscape-scale carbon responses to management changes and ecosystem modifications.[85−87] High-resolution remotely sensed proxies for photosynthesis, like reflected near-infrared,[32] solar-induced fluorescence,[88−90] and photochemical reflectance index,[91] can be measured contemporaneously at flux towers and from satellites, offering a multiscale comparison of carbon exchange under different management regimes.[92] Airborne and satellite LiDAR[93−95] provide a rich set of tools to allow fluxes to be mapped across heterogeneous canopy types and structures[96−98] for NCS strategies with predominantly aboveground carbon stock changes. NCS ecosystems that depend on changes to belowground carbon pools, like agricultural ecosystems, could also benefit from a multiscale approach.[99]

To achieve widespread and spatially explicit NCS quantification, gridded products derived from the current Fluxnet database[100−102] could quantify the baseline potential carbon uptake. This carbon uptake potential parallels the widely used concept of potential evapotranspiration, which parametrizes a generic herbaceous land cover to derive actual evapotranspiration across biomes (e.g., ref 103). Against this biogeochemical baseline, novel management treatments could be compared in an effort to gauge the net impact of a given NCS strategy.

The flux networks, already leaders in open-source data sharing, should develop data aggregation tools and ancillary data streams that bring network data to bear on specific NCS strategies and encourage future long- and short-term deployments that fill the data gaps. With a transition from project-based carbon accounting to broader jurisdictional approaches that better address carbon "leakage"[104] and are more aligned with the necessary scale of carbon removal, eddy covariance networks are well-positioned to contribute to upscaling the climatic impact of regional NCS.

Monitoring Policy-Compliant Projects. Implementation of climate policy that regulates or financially incentivizes carbon avoided or removed by NCS projects typically requires a precise accounting of a project's net GHG fluxes. If every NCS project could be constantly monitored with ecosystem-scale flux measurements, compliance schemes would be able to precisely quantify the year-to-year carbon performance of each project, compared to a nonintervention baseline, and align financial rewards accordingly. However, eddy covariance has generally not been feasible for this kind of compliance environment because of its complexity and cost relative to the monetary value of avoided or sequestered carbon. (A few approved voluntary GHG quantification methodologies, like that for restored deltaic wetlands, do allow for the use of eddy covariance measurements.[105])

Costs have dropped precipitously over recent years; commercial and open-source softwares have made site setup[106] and data processing[107−109] more accessible and turnkey. Even so, a basic eddy covariance measurement system can still cost multiple 10s of thousands of USD in short-statured ecosystems, and substantially more where tall towers are required to extend above a forest canopy. These technologies have traditionally been designed for research; investment in project monitoring using eddy covariance could spur innovation toward lower cost instruments that capture the key metrics at a fraction of the cost.[110,111] Recent technological innovations, for example, have democratized air quality measurements by introducing low-cost sensors that, while relying on less precise methods (e.g., laser particle counter instead of mass-based measurements), allow for much broader spatial coverage and access to localized data.[112]

Justifying the cost of eddy covariance's high spatial and temporal resolution at the project scale requires a favorable combination of emission reduction density, carbon prices, and required precision. Eddy covariance measurements can resolve annual carbon stocks on the order of 0.5 tC ha^{-1} (50 gC m^{-2})[113,114] integrated over a management-relevant spatial scale of 100−1000 ha. An NCS project that permanently enhances sequestration by 2 $\mathrm{tCO_2e\ ha^{-1}\ yr^{-1}}$ over 1000 ha, for example, is worth about $100,000 USD annually, at a carbon price of $50 USD per $\mathrm{tCO_2e}$ (United States' social cost of carbon in year 2030[115]). At lower levels of precision, quantification methodologies often take a conservative approach to credit allocation, resulting in fewer credits. In some cases, direct GHG measurements could result in crediting a larger fraction of the benefits and have been shown to boost profitability.[36] Others have argued that continuous, direct measurement of project-based NCS performance can increase certainty and reduce invalidation risks.[37]

Compliance schemes that value a more diverse range of ecosystem services beyond carbon removal, like water availability or local surface temperature regulation, or put a higher value on measurement precision and real-time reporting, would better take advantage of the range of insights flux towers offer for NCS projects. The cost and complexity of eddy covariance deployment makes it unlikely to replace traditional inventory approaches at the current economic valuation of ecosystem carbon removal. Nonetheless, strategic comparisons of traditional inventory versus eddy covariance-measured carbon removal estimates could be useful for identifying opportunities for more targeted model and methodological improvements, for example in NCS strategies where the two methods diverge most.

4. CONCLUSION

Climate change solutions that harness natural and working lands hold much promise and major uncertainties. As the most complete and direct method to measure ecosystem-scale fluxes, eddy covariance has an important role to play in prioritizing, measuring, and monitoring the implementation of NCS. A significant portion of the global potential for NCS could come from ecosystems for which traditional carbon accounting approaches are incomplete or impractical (Table 1). We suggest prioritizing eddy covariance implementation to improve the accuracy, reliability, and scalability of NCS quantification.

We especially recommend applying ecosystem-scale flux measurements to NCS strategies characterized by hidden or inaccessible carbon pool changes, important non-$\mathrm{CO_2}$ GHG fluxes, potentially large-scale biophysical feedbacks, or difficult-to-predict successional changes (Figure 1). These NCS characteristics describe many wetland, peatland, grassland, and agricultural NCS activities. Although often undervalued compared to forest NCS, these emerging strategies account for a significant portion of the global potential (Table 1), but require a more sophisticated toolkit to measure and monitor effectively.

Our framework describes three deployment types that serve different needs and scales (Table 2). "Pilot" deployments, combined with complementary measurements, already allow for high precision emission reduction potentials for specific NCS activities. "Upscaling" holds great potential to intentionally deploy eddy covariance as anchors for a multitechnique scaling approach that integrates over spatially heterogeneous landscapes and NCS solution portfolios. Finally, "monitor" deployment could one day be the standard for quantifying policy-compliant performance of NCS projects, especially those that involve fluxes and trace gases overlooked by traditional inventory techniques.

The need for accurate, affordable, and accessible accounting of the true impact of NCS, in the face of widespread ecosystem heterogeneity and ongoing climate change, is a key priority if NCS are to realize their potential. The integration of ecosystem scale flux measurements by the NCS community, and the prioritization of NCS measurements by the flux community, together have the potential to capture the net impacts, unintended feedbacks, and on-the-ground specifics of novel NCS strategies.

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Notes

The authors declare no competing financial interest.

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