

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

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3 **Running title:** *Informing Nature-based Climate Solutions*

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

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

68

69 **1. Overview:**

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

83

84 In the U.S., intentional implementation of NbCS has been relatively limited, and largely organized  
85 around private voluntary carbon markets (Anderegg 2021, Seddon et al. 2021, but see CNRA 2021),  
86 which offer the promise of revenue streams for landowners and for private entities focused on project  
87 development and monitoring. Forest carbon offset projects in California’s compliance system perhaps  
88 represent a more systematic attempt at coordinated NbCS implementation (Anderegg et al. 2020), though  
89 the actual mitigation achieved through these projects is not clear (Badgley et al. 2021). However, looking  
90 forward, state- and federal agencies appear poised to authorize large investments in NbCS programs  
91 (Fargione et al. 2019, Fleishman et al. 2020, Seddon et al. 2020a). For example, the U.S. Senate passed

92 the “Growing Climate Solutions Act” in 2021, and in early 2022, the USDA released a \$1 billion call  
93 for proposals for “Climate-Smart Commodities.” Indeed, it is an unusual coalition, including  
94 conservation groups, farmers, foresters, bipartisan groups of lawmakers, and private start-ups and  
95 industry, that is driving momentum in the NbCS sphere.

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

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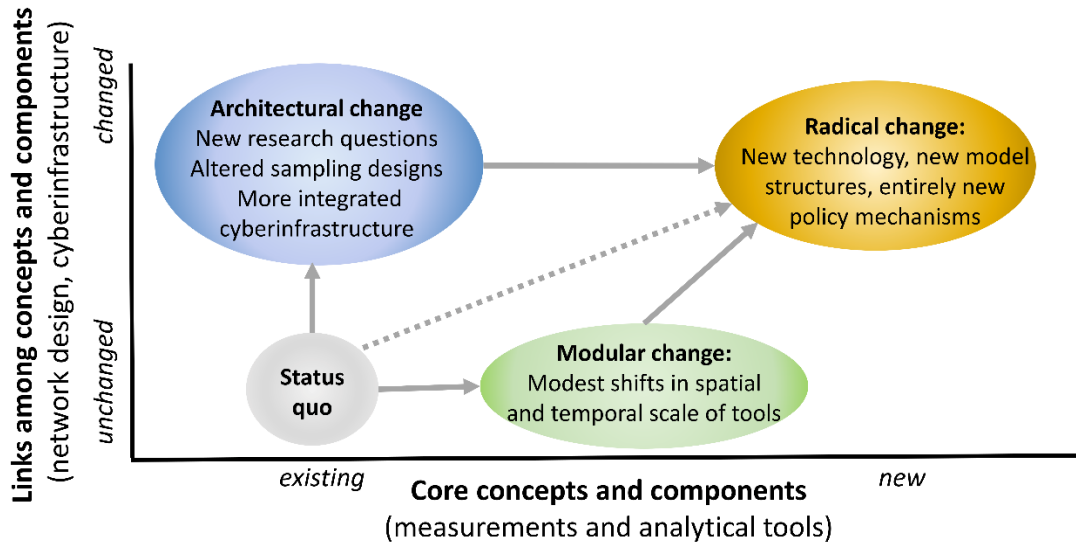
108 The situation becomes even more poorly constrained looking forward, when climate-driven feedbacks  
109 threaten the permanence of carbon stored in many ecosystems. In forests, the large amount of carbon  
110 stored in aboveground plant biomass is threatened by increasing drought, wildfires, and insect outbreaks  
111 (Anderegg et al. 2020, Coffield et al. 2021); in soils, warming can stimulate decomposition and CO<sub>2</sub>  
112 fluxes (Hicks Pries et al. 2017). The Earth System Models (ESMs, Heavens et al. 2013) used to couple  
113 interactions between ecosystems and the climate system account for these feedbacks, but the simpler  
114 models used for NbCS benefit evaluation do not. Finally, all this uncertainty propagates into operational

115 barriers hindering NbCS project implementation within carbon markets. That process generally relies on  
116 statistical models and biometric soil and tree survey data collected over relatively long timescales  
117 (typically 5+ years). The resource-intensive nature of biometric inventories, along with the relatively  
118 low price of carbon, practically excludes all but the largest non-tenant producers and landowners from  
119 participating. The approach also exposes the system to risks associated with unduly optimistic  
120 assessments of project benefits or practice implementation (Badgley et al. 2021).

121

122 Our objective is to identify knowledge gaps surrounding NbCS that may be confronted, over the short  
123 term, with pre-existing data, infrastructure, and tools that have long been used to measure and predict  
124 ecosystem-scale GHG exchanges, but have not yet been harnessed for what they reveal about NbCS  
125 effectiveness. We contend that new perspectives on NbCS climate benefits and unintended consequences  
126 can be largely enabled by relatively subtle shifts in the scales at which these existing tools are applied  
127 (e.g., “modular innovation”) and blended together (e.g. “architectural innovation, *sensu* Henderson et al.  
128 1990, see Figure 1). However, for some uncertainties, and especially those surrounding NbCS  
129 permanence, more “radical” shifts in approach may be required. Collectively, the perspectives presented  
130 here could function as a proposal describing the work needed to inform NbCS assessments with the best-  
131 available science.

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

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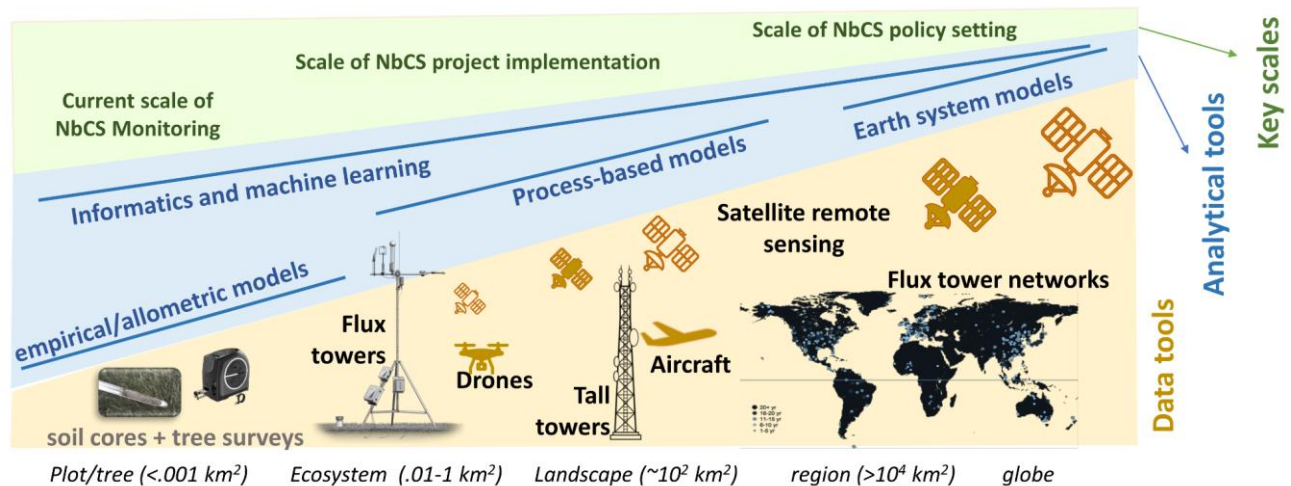
139 **2. NbCS-relevant data and analytical tools:**

140 The dominant role of terrestrial ecosystems in determining the fate of atmospheric CO<sub>2</sub> has been known  
 141 for decades. Consequently, huge investments of resources have fostered the development of innovative  
 142 tools for monitoring and quantifying ecosystem carbon cycles (Figure 2). These include tools for  
 143 quantifying both carbon stocks (or the amount of carbon stored in soil, litter, or plant biomass) and  
 144 carbon fluxes (which represent the rates at which carbon is transferred into, out of, and within  
 145 ecosystems). While fluxes can be inferred from the change in stocks over time, this approach only works  
 146 if all the relevant stocks are measured (which is often infeasible). Moreover, carbon stock data alone are  
 147 insufficient to reveal the processes responsible for a change in carbon uptake, or to estimate emissions  
 148 of non-CO<sub>2</sub> greenhouse gases like methane and N<sub>2</sub>O. Right now, the vast majority of the existing

149 approaches for flux measurement and modeling are not being widely applied to NbCS evaluations.  
150 Particularly striking is the fact that the only direct observations of land-atmosphere carbon, water, and  
151 energy exchanges (from flux towers, Baldocchi et al. 2008) have not yet been systematically assessed  
152 for what they can tell us about NbCS impacts (Hemes et al. 2021). Likewise, many next-generation  
153 remote sensing products and state-of-the-art process-based models are also not being widely used to  
154 inform NbCS policy making or implementation.

155

156 A general tradeoff exists between the accessibility of these tools to broad communities of stakeholders,  
157 and the robustness with which they describe a full set of relevant ecosystem processes (Figure 3).  
158 Biometric soil core and tree survey data are simple, low-cost measurements that are broadly accessible;  
159 however, their robustness is limited, as they do not account for all carbon stocks, provide little  
160 information about biophysical impacts, and have a low temporal resolution that limits their ability to  
161 detect changes quickly. In contrast, flux towers have a high degree of “robustness” linked to their ability  
162 to continuously measure the net flux of CO<sub>2</sub> (and other GHGs) between the atmosphere and the  
163 ecosystem, as well as a full suite of related water and energy cycle variables. But flux towers are  
164 expensive, and quality control and post-processing of flux tower data has historically required specific  
165 expertise. Satellites and drones provide spatially robust proxies for NbCS-relevant variables at scales  
166 that are increasingly well- matched to farms and fields. However, the temporal resolution of these  
167 products is often limited, and no technology yet exists to measure the net flux of CO<sub>2</sub> or other GHGs  
168 directly from space.



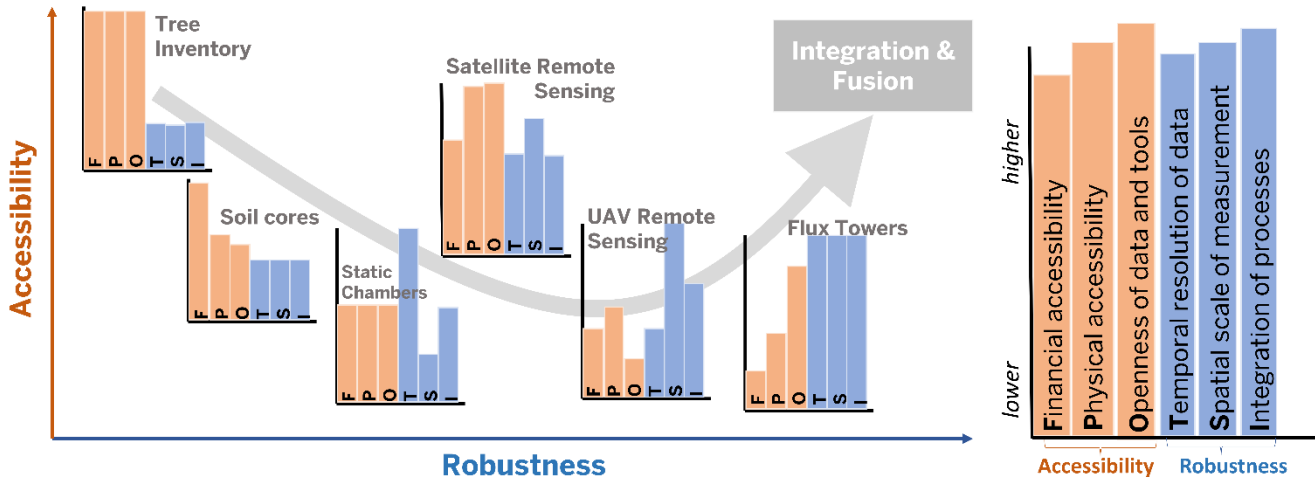
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170 *Figure 2: Existing tools and approaches for quantifying carbon pools and GHG emissions from*  
 171 *terrestrial ecosystems. See Supplementary Information (S.I.) for detailed description of each tool.*

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173 The extent to which data are “open” and discoverable to a wide range of researchers and stakeholders is  
 174 another dimension of accessibility. Flux tower networks like AmeriFlux, FLUXNET, and NSF’s  
 175 National Ecological Observatory Network (NEON) have long been on the forefront of open data sharing  
 176 (Baldocchi et al. 2009, Novick et al. 2018, Metzger et al. 2019). Tree inventory data from the USDA  
 177 Forest Inventory and Analysis (FIA) program (Bechtold & Patterson 2005) are also highly standardized  
 178 and accessible, and soil carbon data are also becoming more aggregated and open (Arias-Ortiz et al.  
 179 2021a, Bond-Lamberty et al. 2020, Malholtra et al. 2019). However, by and large, these networks are  
 180 not well connected to each other digitally, and with limited physical overlap between network sites that  
 181 hinders synthesis (Hinckley et al. 2016).





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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.

198 **3: Informing NbCSs with a full set of tools and approaches:**

199 **3.1. NbCS assessments at policy-relevant scales:** Policymakers and stakeholders need regional- to  
200 global-scale assessments of the expected mitigation potential of NbCS, including information about  
201 when and where a given approach is most likely to succeed. Ideally, these assessments fulfill the  
202 following criteria: 1) they are *informed by* observations of land-atmosphere GHG fluxes *made directly*  
203 *at the ecosystem scale* (~ 1 km<sup>2</sup>), thereby integrating over multiple above- and belowground GHG  
204 sources and sinks; 2) they are *spatially resolved* (e.g. mapped) and describe *where* the benefits of a given  
205 NbCS are greatest; and 3) they are *forward looking*, with careful consideration of the durability of  
206 benefits into a future characterized by pervasive climate feedbacks. Right now, a wide gulf separates  
207 available information from these idealized criteria. The following subsections highlight ways that flux  
208 tower data, survey data, remote sensing data, and models can be used together to narrow the gap. An  
209 emergent theme will be the need for “*gold-standard datasets*” to support a wide array of NbCS  
210 assessment and validation goals. We imagine these datasets would represent standardized, open and  
211 accessible observations of a full suite of carbon stock and flux measurements, from NbCS “treatments”  
212 as well as baseline controls, together with information about historic land use. Sustaining long-term flux  
213 tower data records should also be a priority, since substantial knowledge gaps remain surrounding the  
214 extent to which ecosystem carbon uptake may “saturate” in time (Craig et al. 2021, Curtis & Gough  
215 2018, and see additional text in the S.I.).

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217 **3.1.1. Systematic evaluation of ground-based observations:**

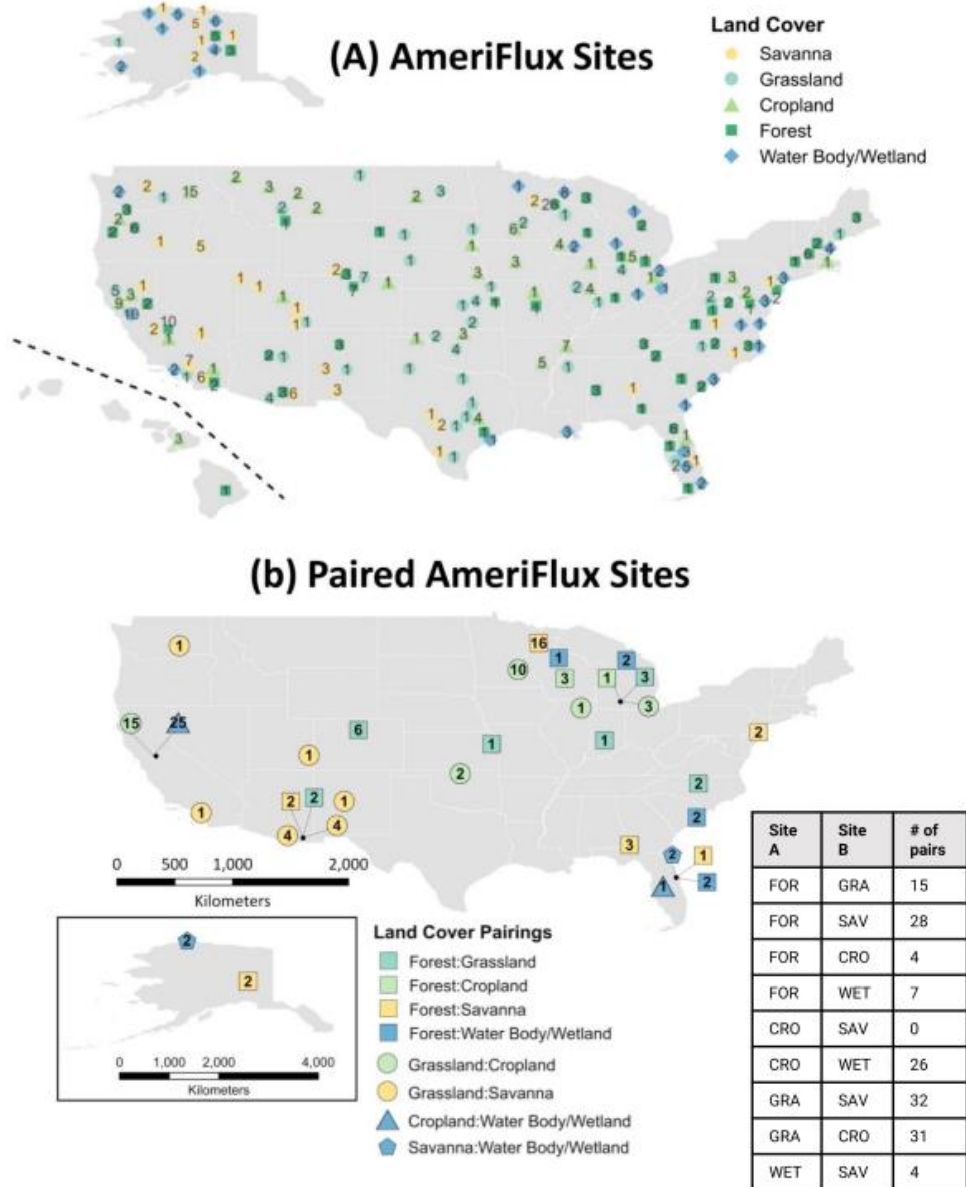
218 **Forests** In forests, which contain a variety of species at different stages of growth, the ability of flux  
219 towers to integrate over all carbon sources and sinks is extremely useful. Multi-year time series from

220 >150 flux towers located in forests are already available from AmeriFlux; of these located in the United  
221 States, several dozen represent forests or tree-dominated savannahs co-located with grasslands or  
222 croplands (Fig. 4), offering an opportunity for a first-order, ecosystem-scale assessment of the realizable  
223 mitigation potential of reforestation as an NbCS. However, the relatively high costs of building and  
224 maintaining tall forest towers will always limit their spatial representativeness. In contrast, tree survey  
225 data are relatively abundant, thanks to programs like FIA, and may be adequate in some regions to  
226 quantify spatial patterns in aboveground biomass (Hemes et al. 2021). However, tree surveys have long  
227 (5+ year) sampling intervals, and do not capture patterns of belowground carbon cycling and storage.  
228 Comparing tower-based carbon fluxes with estimates derived from biometric survey data from the same  
229 site (e.g. Wang et al. 2017, Campioli et al. 2016) can be useful for understanding the biases in carbon  
230 uptake potential informed by biometric tree survey data alone. Adding routine biometric sampling (soil  
231 cores, tree surveys) to active forest flux tower sites would represent a relatively low-cost initiative that  
232 could form the foundation of “gold-standard” datasets for forested NbCS.

233

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

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241

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

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249 ***Croplands:*** Because they are already intensely managed, croplands represent relatively “low hanging  
250 fruit” for NbCS implementation. Climate mitigation benefits of croplands are largely constrained to soil  
251 carbon pools, as the majority of aboveground biomass is removed by harvest. While soil carbon is  
252 theoretically easy to measure, creating sampling strategies that adequately capture horizontal and vertical  
253 heterogeneity in soil carbon, and its change over time, remains difficult and expensive (Smith et al.  
254 2020). Critically, soil carbon data alone are insufficient to identify responsible mechanisms, such as  
255 greater carbon uptake from photosynthesis versus reduced carbon loss in runoff. Concerningly, while  
256 soil carbon data tend to report a soil sequestration benefit from cover cropping (Poeplau & Don 2017),  
257 at least one study leveraging flux tower data reports that cover crops do not favorably impact net carbon  
258 uptake (Baker & Griffis 2005). Moreover, because empirical studies reporting on soil carbon changes  
259 are limited for many categories of NbCS, spatially explicit maps of cropland NbCS mitigation potentials  
260 do not yet exist. Consequently, we do not know where climate conditions favor or disfavor these  
261 strategies.

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

271 design around existing cropland flux towers with soil carbon monitoring, outflow monitoring, and static  
272 chambers is a relatively straightforward path for creating “gold-standard” datasets for cropland NbCS.

273 **Wetlands and coastal systems:** Inundated and/or saline conditions provoke a decline in carbon  
274 mineralization and offer an opportunity for enhanced soil storage of carbon. Tidal wetland restoration is  
275 an especially promising wetland solution (Kroeger et al., 2017; Fargione et al., 2018), and together with  
276 seagrass restoration (or avoided loss), represents significant potential for coastal landscapes (~25 Tg  
277 CO<sub>2</sub>e yr<sup>-1</sup>). Away from the coasts, riparian zone and peatland restoration (Vermaat et al. 2021, Gunther  
278 et al. 2020a), and methane emissions reduction in rice (Runkle et al., 2018) represent additional  
279 opportunities for managed wetlands to contribute to climate solutions. A particular challenge for NbCS  
280 is optimizing carbon uptake and sequestration of existing soil carbon against possible production of CH<sub>4</sub>  
281 and N<sub>2</sub>O (Hemes et al., 2018; Rosentreter et al., 2021; Valach et al., 2021) and biophysical effects (Lee  
282 et al., 2021).

283 Flux towers are well-positioned to assess these impacts, as they enable measurement of complementary  
284 gases (CH<sub>4</sub>, N<sub>2</sub>O) at a high temporal resolution that enables detection and interpretation of spikes (often  
285 called “hot moments”) of gas release associated with sudden changes in water levels or biological  
286 conditions (Turner et al. 2021). They must be placed alongside estimates of lateral carbon flows (Bogard  
287 et al. 2020, Arias-Ortiz et al. 2021b) and then analyzed in concert with tidal or water flow data. Like  
288 many agricultural sites, the shorter vegetation in these landscapes may reduce some costs, and site  
289 management may be conducive to paired or clustered site experimentation. Indeed, more sites are needed  
290 to capture the impact of different hydroperiods, vegetation, and biogeochemistry (Matthes et al., 2014);  
291 blue carbon flux sites are also only one-third as prevalent as forest, agriculture, or grassland sites (Hemes  
292 et al., 2021).

293

294 **3.1.2: Blending flux tower data with state-of-the-art remote-sensing observations:**

295 Remote sensing data is indispensable for extending ground-based observations to scales relevant for  
296 policy making. Already, remotely-sensed proxies for aboveground biomass are being used to map forest  
297 carbon stocks (Rodriguez-Viega et al. 2017), and next-generation laser and radar missions (Ustin &  
298 Middleton 2021) will produce high-resolution (25 m – 200 m) and three-dimensional biomass estimates  
299 of the world’s forests. In croplands, remote sensing is already proving useful for detecting the  
300 presence/absence of NbCS-relevant management practices like cover crops and no-till management  
301 regimes (Azzari et al. 2019, Barnes et al. 2021), as well as crop yield (Guan et al. 2017) - a major carbon  
302 cycle “flux.” However, while maps of carbon stocks and practice adoption rates provide useful  
303 information for NbCS policy evaluation, they are not the same as maps of the potential of a management  
304 practice to avoid emissions and enhance sequestration. The change in remotely-sensed biomass over  
305 time can be blended with allometric equations to infer the flux of CO<sub>2</sub> from the atmosphere to  
306 aboveground vegetation (Rodriguez-Viega et al. 2017, Quegan et al. 2019). But these approaches are  
307 generally only possible for forest ecosystems, and they suffer from the same biases affecting biometric  
308 tree surveys.

309

310 Progress towards spatially explicit maps of NbCS mitigation potential could be enabled by a growing  
311 suite of spaceborne instruments, so-called “Flux Towers in the Sky” (Schimel & Schneider 2019), which  
312 can sense key aspects of plant function. These next-generation platforms include: a) solar-induced  
313 fluorescence (SIF), which is physiologically related to the rate of photosynthesis (Magney et al. 2021),  
314 b) column-averaged atmospheric CO<sub>2</sub> which can be used for “inverse” estimates of land carbon fluxes  
315 (Wang et al. 2019), and c) instruments for sensing ecosystem water stress (e.g., ECOSTRESS, Fisher et

316 al. 2020, and microwave data on canopy water content, Konings et al. 2021). While the spatial resolution  
317 of these satellite products can be coarse, some are now available at scales that match those of individual  
318 farms (e.g. ECOSTRESS, Fisher et al. 2020), and the need for finer-scale versions of other products has  
319 been clearly articulated (Konings et al. 2021). In many cases, substantial increases in resolution are  
320 possible with drone-mounted instruments (e.g. SIF, Mohammed et al. 2019). The information provided  
321 by these platforms is sensitive to limitations and biases, which are well-reviewed elsewhere (Konings et  
322 al. 2020, Fisher et al. 2020, Magney et al. 2020), and will continue to benefit from validation with flux  
323 tower data (e.g. Sun et al. 2017, Fisher et al. 2020), including novel strategies for fusing data across  
324 different scales of observation (see Section. 3.3).

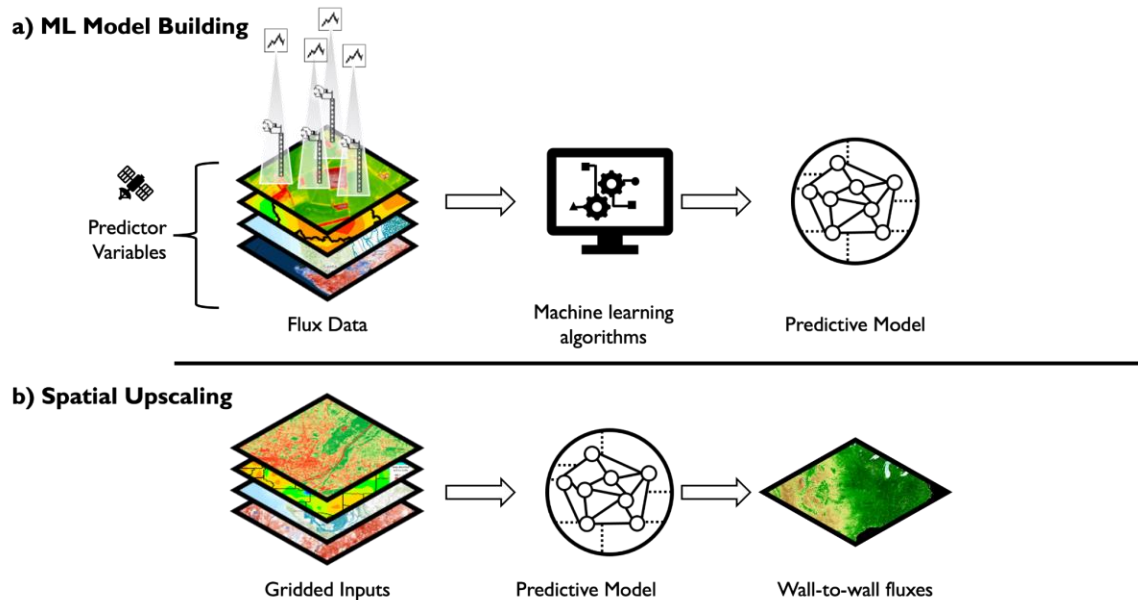
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326 Next-generation remote sensing products can also enable machine learning (ML) extrapolation, or  
327 upscaling, of flux tower data into gridded maps (Figure 5), with the FLUXCOM project representing the  
328 most notable example (Jung et al.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



339 Cyberinfrastructure that links ‘cut-outs’ of remote-sensing products with flux tower data at a given site  
340 could be an important feature of “gold-standard” NbCS verification datasets.

341



342

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

347

348 **3.1.3 Models.** Spatially explicit and forward-facing NbCS assessments are not possible without the use  
349 of predictive models. Indeed, models are already used to interpolate ground observations into regional  
350 scale potential maps (e.g. for forest biomass, see Section 3.1.2) and to prescribe the value of project-  
351 scale market credits. But the models used for these objectives are highly empirical (e.g. regression  
352 based), relying on observed relationships between driver and response variables that cannot be  
353 extrapolated into a future characterized by climate conditions profoundly different than those  
354 experienced historically.

355

356 Earth system models (ESMs), which predict future climate states for a range of anthropogenic emission  
357 scenarios, are currently the only tool for mechanistic prediction of climate-ecosystem feedbacks, and the  
358 only way to estimate the net effect of the combined physical and biogeochemical impacts into the future.  
359 The land component of ESMs -- “Terrestrial biosphere models” (TBMs) -- come in many flavors (Fisher  
360 et al. 2018), but they are generally constrained by fundamental conservation laws and rely on  
361 biogeochemical and biophysical theory to predict flows of carbon, water and other elements through the  
362 natural world (see Supplementary Information, hereafter S.I., for an extended discussion).

363

364 TBMs have not yet been widely applied to assess NbCS impacts, which may relate to the fact that TBMs  
365 were initially developed to transfer fluxes of energy, moisture, and momentum to the atmosphere, with  
366 prognostic carbon cycling largely developed in the 2000s (e.g., Cox et al. 2000; Fung et al. 2005). The  
367 inclusion of management-relevant processes, including land use change, agriculture, and nutrients, came  
368 even more recently (Fisher and Koven 2020). The models are still limited by their capacity to represent  
369 management and disturbance processes, and in their skill at quantifying avoided emissions of non-CO<sub>2</sub>  
370 GHGs in agriculture. Addressing these limitations is an active research field. For example, mechanistic  
371 representation of species demographics and climate-sensitive disturbances like fire are rapidly being  
372 implemented in TBMs (Fisher et al. 2018). With respect to agricultural systems, several TBMs now  
373 include a basic, but coarse, representation of agricultural and pasture management (Lombardozzi et al.  
374 2020, Pongratz et al. 2018), and TBMs have been used to explore coarse-scale tradeoffs and unintended  
375 consequences associated with managed land cover change (Harper et al. 2021, DuVeiller et al. 2020).  
376 Thus, despite their limitations, TBMs are very useful for general assessments of when and where NbCS  
377 are likely to be most effective (see, for example, Graham et al. 2021, Harper et al. 2018)

378

379 However, substantial gaps must be addressed before process-based models can be fully applied to the  
380 many pressing sources of NbCS uncertainty, and in particular uncertainties linked to the spatial  
381 resolution of the models and their ability to predict the permanence of NbCS benefits. Right now, TBM  
382 spatial resolution is typically too coarse to resolve the field and farm scales where carbon credits are  
383 assessed and monitored. Moreover, future projections of land carbon uptake are very uncertain in ESMs,  
384 particularly into the latter half of the 21<sup>st</sup> century (Arora et al. 2020). Put simply, the models do not agree  
385 on the magnitude, and in some cases the direction, of future land-carbon uptake at the global scale  
386 (Friedlingstein et al. 2014). This fundamentally large and potentially irreducible uncertainty (Bonan &  
387 Doney 2018) poses major challenges for predicting NbCS permanence. While radical changes to model  
388 structure and parameterization may help, several very pertinent questions remain relatively unexplored:  
389 First, will the uncertainty problem be reduced when models are tasked with predicting the \*change\* in  
390 land carbon uptake driven by a specific NbCS approach, as opposed to the absolute magnitude thereof?  
391 Can this uncertainty be priced into the market systems? And to what extent is model agreement improved  
392 when assessed at landscape and regional (as opposed to global) scales? Progress on the latter question  
393 may be facilitated by model-data assimilation approaches for near-term “ecological forecasting” (Dietze  
394 2017) and landscape scale model-data fusion (see Section 3.3).

395

396 **3.2. Towards generalizable frameworks for assessing biophysical co-benefits and/or unintended**  
397 **consequences.** Ecosystem carbon uptake is closely coupled with ecosystem water use, such that a  
398 managed alteration to land cover designed to affect C cycling will also affect the local hydrology. In  
399 general, greater C uptake will likely be associated with greater evapotranspiration (or ET); whether or  
400 not this is a favorable biophysical impact depends on climate regime, time of year, and management

401 intent. For example, an increase in ET in spring may be welcomed by farmers throughout much of the  
402 Corn Belt, when the primary soil water problem is usually one of overabundance (e.g. flooding, Yin et  
403 al. 2020). On the other hand, when and where soil moisture deficits are common, NbCS-driven increases  
404 in ET that further deplete soil moisture and runoff may be undesirable. With some exceptions (e.g.  
405 Jackson et al. 2005, Windisch et al. 2021), systematic assessments of tradeoffs between NbCS carbon  
406 benefits and water cycle consequences are rare, and generally not interpreted in the context of predicted  
407 future changes in precipitation and soil moisture balance.

408

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

421

422 Substantial opportunity exists to leverage pre-existing data in networks like AmeriFlux for synthetic  
423 assessments of carbon and biophysical impacts of NbCS, since they measure most terms of the water

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

433

434 **3.3. Accessible and robust market-relevant quantification of project-scale impacts:** Balancing  
435 accessibility and robustness is a pivotal challenge facing quantification strategies for NbCS projects,  
436 typically implemented at scales  $<100 \text{ km}^2$ . Assessments that forgo direct measurement may enhance  
437 accessibility to landowners but run the risk of over- or under-quantifying the true climate benefits,  
438 eroding trust in NbCS claims or missing an opportunity to finance important activities (Gunther et al.,  
439 2018). The most robust quantification - one that would require frequent physical sampling of each carbon  
440 pool over much of the project area - is a Sisyphean task, and will make quantification operationally and  
441 economically inaccessible to the vast majority of landowners. The appropriate balance between  
442 accessibility and robustness will vary among ecosystem and NbCS project types, scales, policy  
443 requirements, and the acceptable level of uncertainty.

444

445 In practice, the typical approach to quantifying NbCS benefits relies on periodically inventorying small  
446 changes to large carbon stocks, and differencing these from the carbon stocks that would have been

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

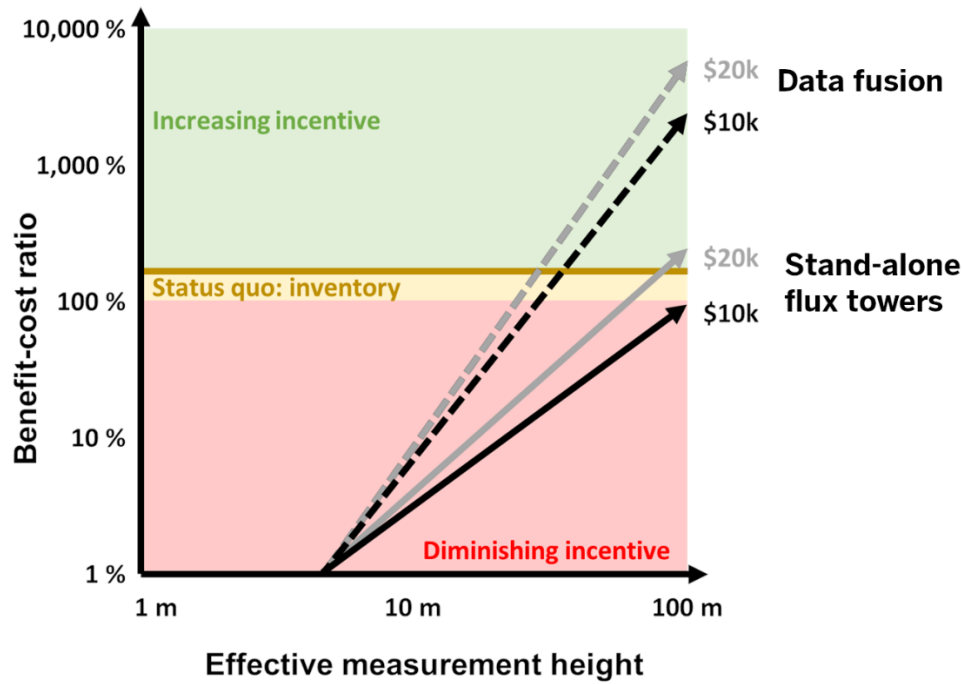
458

459 **3.3.1: Leveraging ecosystem-scale data for monitoring and verification of NbCS projects:** Flux  
460 towers are attractive tools for monitoring and verifying individual NbCS projects. They provide  
461 continuous data on the integrated carbon sources and sinks of an ecosystem, and their high level of  
462 precision ( $\sim 50 \text{ tC km}^{-1}$ , Hemes et al. 2021) can justify the crediting of a larger fraction of the projected  
463 carbon uptake compared to other quantification schemes. Moreover, the rapid response of ecosystem  
464 fluxes to land cover and management changes (e.g, Aguilos et al. 2020) can reveal the impacts of an  
465 NbCS intervention faster than inventorying slowly-evolving biomass and soil carbon pools.

466

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

470



471

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

478

479 market value (representing the combined influence of sequestration potential and price of carbon) and  
480 the effective tower measurement height (which determines monitoring cost as well as the size of the  
481 measurement footprint, Chu et al. 2021). The analysis adopts the conservative constraint that flux towers  
482 should continuously monitor a project area of 1 km<sup>2</sup> (even if that requires the use of multiple towers via  
483 an economy of scale) for a project lifetime of 30 years. The project market value was initially set to  
484 ~\$10,000 km<sup>-2</sup> yr<sup>-1</sup>, based on an ‘additional’ sequestration of 200 tCO<sub>2</sub>e km<sup>-2</sup> yr<sup>-1</sup> and a price of carbon

485 at \$50 per tCO<sub>2</sub>e, and reference annualized costs representing status-quo monitoring approaches were  
486 set to \$7,000 km<sup>-2</sup> y<sup>-1</sup> (see S.I. for details). On this basis, the reference BCR was estimated to be ~140%,  
487 i.e. the revenue created by the project exceeds its cost by 40%.

488

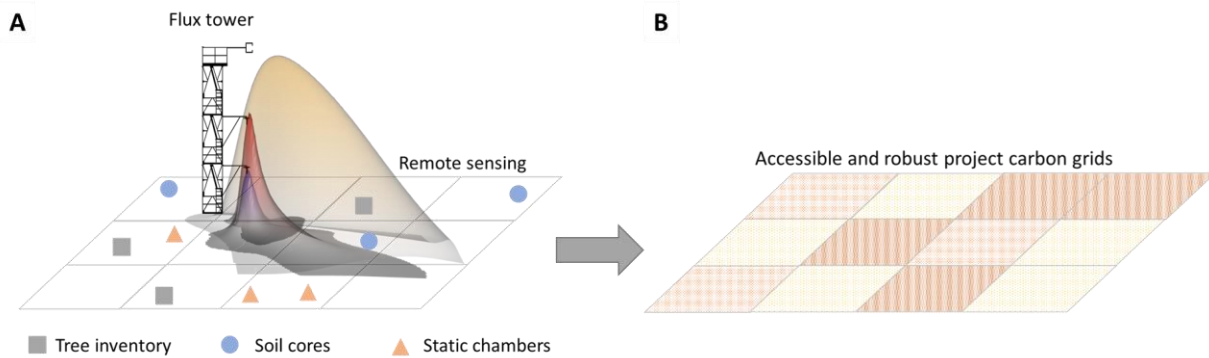
489 While the BCR increased as a function of effective measurement height, even a tall tower (~100 m) did  
490 not reach cost-neutrality (BCR = 93%, Fig. 6). BCR also increased as a function of the project market  
491 value, but not enough to motivate the use of standalone towers as a monitoring tool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

496

497 Substantial opportunity also exists to fuse flux tower data with complementary biometric observations  
498 (e.g., Harris et al. 2021; Smith et al. 2020) which can improve the BCR. Specifically, the development  
499 of comprehensive physical “Carbon Observing and Data Analysis Systems” (CODAS, see Figure 7) can  
500 enable scaling from measurement plots to ecosystems to landscapes with rigor, and also provide  
501 information on the processes that flux towers can not see (e.g. lateral runoff, or non-CO<sub>2</sub> GHG emissions  
502 that are below instrument detection limits, Detto et al. 2011). In CODAS, data integration and scaling  
503 can be achieved with the use of so-called “environmental response functions” (ERFs, Metzger et al.  
504 2013, 2018). The underlying principle of ERF is to use high-frequency (minute to minute) tower  
505 footprint variation to extract the relationships between tower-measured fluxes, meteorological forcing  
506 variables, and surface ecological and soil properties. Then, these extracted relationships can be combined  
507 with remote sensing data to create half-hourly, decameter-resolution carbon flux grids (e.g., Metzger et



508 al., 2013; Xu et al., 2017, Fig. 7), improving accuracy and precision for geographically representative  
509 and integrated impact assessments. Importantly, this virtual extension of the tower footprint substantially  
510 improves the BCR, such that the status quo BCR can be exceeded for measurement heights on the order  
511 of 30 m or greater (Fig. 6) even when carbon prices are relatively low (see S.I. for more details).



512  
513 *Figure 7: A Carbon Observing and Data Analysis System (CODAS) integrates multi-scale observations*  
514 *to accessible and robust project carbon grids. Panel A: Flux tower CODAS reconciles the differing*  
515 *contexts in space and time among ground-based, airborne and spaceborne carbon observations: data*  
516 *fusion aims to harnesses the benefits and offset the limitations among the individual observation*  
517 *methods, thus fully utilizing their joint information to quantify NbCS project performance. Panel B: The*  
518 *results are project carbon grids at half-hourly and decameter resolution with reduced cost per unit area*  
519 *and improved robustness compared to any individual observation method alone. This near-real time*  
520 *spatialization enables continuous assessment and optimization of localized management practices, and*  
521 *timely intervention for underperforming plots within the NbCS project area.*

522  
523 Novel quantification approaches like ERF data fusion require validation. Here, multi-scale  
524 benchmarking approaches originating from earth system modelling can provide a useful path forward.  
525 For example, the International Land Model Benchmarking (ILAMB) package (Collier et al., 2018) was  
526 originally designed to evaluate and benchmark land model results through comparison with site-,

527 regional-, and global-scale observations, including from airborne CO<sub>2</sub> concentration measurements (Cui  
528 et al. JGR-A in press), satellite-based remote sensing (Eldering et al., 2017), machine-learning flux  
529 upscaling products (Jung et al. 2019), and carbon cycle models and data assimilation products (e.g.,  
530 NOAA CarbonTracker, Peters et al., 2007). When referenced to CODAS ground-truthing data,  
531 benchmarking systems like ILAMB could provide an important perspective on the magnitude and  
532 uncertainty of realized NbCS project benefits, as estimated from a range of ground-, airborne-, and  
533 spaceborne observations.

534

### 535 **3.3.2: Gold-standard datasets for transparent, reproducible, and objective validation of existing**

536 **valuation schemes:** Right now, most carbon market protocols use a combination of physical data and  
537 empirical models for carbon credit valuation, and then rely on independent, third-party verification to  
538 ensure methodological standards are met. These verifications tend to be costly, lack standardization and  
539 transparency, and do not include truly independent validation based on alternative methods. Multi-scale,  
540 integrated, “gold-standard datasets” from representative flux tower sites could be used to validate and  
541 improve market verification schemes, especially if they include concurrent observations of carbon  
542 stocks, fluxes (from towers and including lateral exports in runoff), and near-surface and satellite remote  
543 sensing data. Since carbon accounting seeks to measure CO<sub>2</sub> removals or avoided emissions that are  
544 additional to the baseline, gold-standard datasets would be most useful if they: a) capture both pre- and  
545 post-intervention periods, b) rely on paired-sites (pairing an NbCS treatment with a baseline control that  
546 experiences the same macroclimate), and/or c) are developed in ways that leverage the ERF benefit of  
547 localizing fluxes across heterogeneous landscapes.

548

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

556

557 Many tower sites are already collecting some combination of biometric data, including measurements of  
558 soil C pool size, tree biomass, and/or chamber based emissions (e.g. Wang et al. 2017, Campioli et al.  
559 2016, Hollinger 2021) which themselves may be shared to AmeriFlux to other relevant networks (e.g.  
560 the International Soil Carbon Network, Malholtra et al. 2019, or the COSORE soil respiration network,  
561 Bond-Lamberty et al. 2020). However, few sites are recording and sharing the full set of observations  
562 that would be most useful for robust assessments of NbCS. Moreover, with some exceptions (e.g. NEON  
563 sites, Metzger et al. 2019), biometric data are not collected at flux tower sites using standardized  
564 protocols. Thus, enhancing at least a subset of existing flux towers with a fuller set of standardized  
565 biometric measurements to create open and accessible gold-standard datasets should be a priority moving  
566 forward.

567

568 The “gold-standard” datasets described here would provide a critical resource for systematic evaluation  
569 of existing accounting schemes currently in use in private carbon markets, which vary substantially from  
570 one market or entity to the next (see S.I. for details). One way to do this is through model-  
571 intercomparison projects (MIPs), which compare predictions from a variety of models driven by the

572 same forcing data. The flux research community has substantial experience performing MIPs to  
573 benchmark and cross-compare TBMs (e.g. Huntzinger et al. 2013, Friedlingstein et al. 2020). To our  
574 knowledge, no such activity has been attempted for the diverse array of models used to project and  
575 quantify NbCS project benefits. A “Carbon Market MIP,” supported by the to gold-standard data, would  
576 provide an unprecedented view of when and why the carbon market forecasting schemes differ. It would  
577 also enable the exploration of which physiological and ecological processes matter most for the  
578 application-based questions at hand (e.g. C storage and permanence), and could directly test the  
579 effects of NbCS management actions on these long-term carbon market aims. These information-rich  
580 datasets would also permit a systematic “measurement intercomparison” project, to understand where  
581 and why empirical accounting approaches differ. Prior work comparing flux tower and biometric data  
582 has been limited to forests (Wang et al. 2018, Campioli et al. 2016), and not designed with the specific  
583 goal of evaluating quantification schemes actually used in carbon market systems. Finally, these open  
584 and accessible datasets could also be accessible to private entities (e.g. independent 3<sup>rd</sup> party verifiers)  
585 working to develop new approaches for market-ready accounting protocols.

586

587 **3.3.3: Biophysical impacts and permanence:** NbCS projects that modify local water and energy cycles  
588 in ways that exacerbate the negative consequences of climate change are counterproductive. On the other  
589 hand, NbCS projects that confer adaptative benefits for local hydrology and temperature may be more  
590 “valuable” from a climate mitigation and adaptation perspective. However, strategies to incorporate  
591 biophysical impacts and other co-benefits in carbon market structures are not at all clear (Anderson et  
592 al. 2011), since biophysical impacts tend to be local or regional, whereas enhanced C uptake or reduced  
593 GHG emissions are global benefits. It is also counterproductive to offset CO<sub>2</sub> emissions with carbon  
594 stored in forests that are likely to be decimated by wildfires, drought, or insect outbreaks within a few

595 decades. Viable paths for factoring permanence into carbon credit valuation are also murky: the simple  
596 empirical models used for project accounting do not have a mechanism for considering climate  
597 feedbacks, whereas highly mechanistic Earth System Models do not agree on how climate feedbacks  
598 will impact global land carbon uptake. Rigorous, multi-method approaches to estimating permanence  
599 risks - even if uncertainty is high - are urgently needed.

600

601 For these reasons, incorporating biophysical feedbacks and permanence into market valuation schemes  
602 would likely require radical transformation of accounting and verification protocols, data, and model  
603 structures. In the case of biophysical impacts on energy balance, it may be relatively straightforward to  
604 “put a price” on the local temperature impacts of an NbCS strategy, since changes in both carbon and  
605 energy balance fluxes can be expressed in units of “radiative forcing” (Williams et al. 2021) or CO<sub>2</sub>-e  
606 (Windisch et al. 2011). Moreover, if robust projections of carbon storage permanence and associated  
607 uncertainty become possible at the project scale, market structures should be able to accommodate  
608 some discounting of credits, since protocols already accommodate contributions to “buffer” insurance  
609 pools.

610

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

617 2017). Thus, NbCS projects in the Eastern US that enhance tree cover may be a “safer bet” when  
618 compared to projects in the drought- and fire-prone Western US or Alaska.

619

620 **3.3.4 Inclusivity of solutions:** Developing nations, poorer communities, and black, indigenous, and  
621 other people of color (BIPOC) communities frequently bear the brunt of climate change impacts (Hardy  
622 et al. 2017, Hoffman et al. 2020), while more developed nations and privileged communities often  
623 disproportionately benefit from greater monetization of NbCS and associated research funding (Lamb et  
624 al. 2019). Yet, many indigenous regions across the globe manage large carbon stocks, especially in  
625 aboveground biomass (Walker et al. 2014), which makes these regions especially vulnerable to climate  
626 change (Ramos-Castillo et al. 2017). In addition, continuous discrimination and underrepresentation of  
627 historically minoritized groups is especially prevalent among geoscience research communities (Ali et  
628 al. 2021, Marin-Spiotta et al. 2020). These problems require structural changes within academia, starting  
629 with inclusive mentoring and fieldwork policies, cultural exchanges, more funding opportunities for  
630 BIPOC students and researchers, and changes in the focus of teaching (Ali et al. 2021).

631

632 NbCS activities funded via emission offsets must be structured in a way that does not delay meaningful  
633 decarbonization, most especially in industries whose co-pollutants inordinately impact historically  
634 disadvantaged communities. Moreover, inclusive and equitable practices for NbCS monitoring and  
635 implementation will require: early and transparent engagement with stakeholders, incorporation of  
636 traditional knowledge and cultural values, explicit mechanisms for stakeholder self-determination, as  
637 well as continuous cross-cultural education and training of principal investigators (Ramos-Castillo et al.  
638 2017, Reo et al. 2017, Thompson et al. 2020, Varghese et al. 2021). For example, in ecosystem service  
639 markets, large emphasis has been placed on monetizing the material contributions of ecosystems to

640 human wellbeing (Van Riper et al. 2017). However, for Indigenous communities, these outcomes often  
641 do not meet their objectives, highlighting the need to include social benefits and values to NbCS  
642 solutions (Olander et al. 2018). NbCS projects should also ensure the rights to land ownership, as well  
643 as full transparency of accounting methods to establish accessible, scientifically sound, and sustainable  
644 market options to prevent exploitation of historically underrepresented communities.

645

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

655

656 **4. Summary and Conclusions:** The scientific community certainly has not reached consensus on the  
657 realizable climate benefits of Nature-based Climate Solutions (Fleischman et al. 2020, Anderegg et al.  
658 2020, Seddon et al. 2020). Nonetheless, the surprising enthusiasm for NbCS, coming from an unusual  
659 set of public and private entities, will likely make NbCS strategies a core component of U.S. climate  
660 mitigation policy moving forward. It is imperative that these policies be crafted and implemented with  
661 the best-available science. In this paper, we propose multiple strategies for a modular and structural shifts

662 in research foci that will allow us to confront the most pressing sources of NbCS uncertainty, at both the  
663 project scale and at the regional scales where policy decisions are made. These include:

664

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

671

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

675

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

683



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

690

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

693

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

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