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Submitted text for Washington State's Public Comment Form: **Chapter 173-446 WAC: Cap-and-Invest US Forest Offsets Protocol Informal Comment Period #1**

We appreciate Ecology's engagement with the technical working group and public comments from experts as part of this process and see some improvements in the draft protocol as a result of this process. **We have a number of crucial suggestions for strengthening the scientific rigor of the protocol, which is urgently needed given that offsets must deliver on many core aspects of quality so that weak offsets do not compromise the efficacy of the Climate Commitment Act target of 95% greenhouse gas emission reductions by 2050.** These comments are based on a recent expert synthesis, involving 20 world-leading experts on forest carbon offset protocols, that we led about the crucial components for forest carbon offsets, which can be found below and are also uploaded as attachments. Please see our specific comments below and we look forward to further engaging with Ecology to help provide expertise and data to improve the draft protocol.

Anderegg, W. R., Blanchard, L., Anderson, C., Badgley, et al. (2025). Towards more effective nature-based climate solutions in global forests. *Nature*, *643*(8074), 1214-1222.

#1 RE: <u>Draft rule language (chapter 1730446 WAC)</u>

Regarding crediting periods in WAC 173-446-505, we would encourage the Department of Ecology to promote 5 year crediting periods and baseline reassessment intervals for most project types, as shorter crediting periods limit the time that baselines can be misaligned with actual conditions. The trend across the carbon market is toward more frequent (e.g. 5 year) baseline reassessment intervals. Given the amount of uncertainty within a 10 year time period, we discourage this for all project types, and especially nature-based carbon crediting projects, given the large potential for changing baselines, given uncertainty of natural growth (Brancalion and Holl 2020; Holl and Brancalion 2020) and socio-economic changes that could affect projects.

References:

- Holl, K.D. and Brancalion, P.H.S. Tree planting is not a simple solution. *Science* (2020).
- Brancalion, P. H., & Holl, K. D. (2020). Guidance for successful tree planting initiatives. *Journal of Applied Ecology*, *57*(12), 2349-2361.

Concerning WAC 173-446-520 section 14:

We think that the language "avoidable" and "unavoidable" is a better categorization to differentiate reversals, and encourage the Department of Ecology to apply this language, noting that this is the language likely being adopted by the UNFCCC's draft standard for addressing non-permanence/reversals. Such language is important, as there are examples, such as personal or business insolvency leading to the defaulting of an activity participant on their obligations, which illustrate that while a reversal may not have been intentional, it nevertheless is a result of actions by the activity participant for which they are responsible.

Concerning WAC 173-446-530:

We encourage 5 year verification and crediting periods, given the uncertainty for longer periods.

#2 Re: Proposed Revisions to US Forest Protocol:
We strongly encourage dynamic baselining to take place every 5 years instead of the proposed 10 year interval. Shorter baseline reassessment intervals limit the time that baselines can be misaligned with actual conditions, including changing policies and market dynamics. This would make crediting more scientifically rigorous.

References:

- Haya, B. K. et al. Comprehensive review of carbon quantification by improved forest management offset protocols. Front. For. Glob. Change 6, 958879 (2023).
- Coffield, S. R. et al. Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. Glob. Change Biol. 28, 6789–6806 (2022).
- Stapp, J. et al. Little evidence of management change in California's forest offset program. Commun. Earth Environ. 4, 331 (2023).

Revision 3. Revise leakage rate assumption for IFM projects
We agree that the Department of Ecology should adopt a 40% leakage rate, reflecting the findings of this metaanalysis. This is a positive development and makes the protocol more robust.

Revision 5. Revise property appraisal requirements for avoided conversion projects, including third party verification of appraisal
We agree and think this is a step in the right direction. Appraisers have strong potential conflicts of interest as they are paid by the project developer, which means there is an inherent incentive to inflate carbon estimates to be hired again. This can be the result of the well-established, largely unconscious cognitive phenomenon of self-serving bias, which can result in overcrediting through a more favorable baseline, to make a project appear more additional. **Ideally, such appraisers should be hired by the Department of Ecology instead, so that their financial interest is separate from the project developers.** This is consistent with recommendations in the literature:

Anderegg, W. R., Blanchard, L., Anderson, C., Badgley, et al. (2025). Towards more effective nature-based climate solutions in global forests. *Nature*, *643*(8074), 1214-1222.

Giles, C., & Coglianese, C. (2025). Auditors can't save carbon offsets. *Science*, *389*(6756), 107-107.

Coglianese, C., & Giles, C. (2025). Third-Party Auditing Cannot Guarantee Carbon Offset Credibility. *U of Penn Law School, Public Law Research Paper*, (25-28).

Revision 6. Set buffer pool contributions in consideration of regional risks
The consideration of regional variation of risk is a step in the right direction, but we have serious concerns with the proposed maximum caps and risk reductions. Regarding buffer pool contributions, Haya et al. (2023) found that about 26% was probably a conservative floor for stand-clearing disturbance and timber harvest disturbances in REDD+ projects, while Wu et al. (2023) observed that roughly 36% of area in California's compliance offset projects was

projected to lose carbon over the twenty-first century in a mid-range emissions scenario. Badgley et al. (2022) found that California's compliance forest offset protocol's buffer pool is severely undercapitalized from fire. We have work in review that indicates that buffer pools in California's program may be too small by a factor of 3-9. Therefore, total maximum buffer pool contributions may well need to be over 30% to robustly account for risk.

Critically, the predetermined maximum buffer pool contributions for fire (12%) and biotic risks (8%) are not scientifically defensible or robust. The buffer pool contribution for all risks, especially fire risks, should represent scientifically-assessed risk, and not be limited to a predetermined cap. Furthermore, we urge the Department of Ecology to reconsider the 80% buffer pool contribution reduction offered for implementing risk reduction treatments, which very likely overcompensates for the actual risk reduction accomplished by treatments and is not based on robust scientific evidence. **Risk reduction to buffer pool contribution should be updated to be based on rigorous scientific evidence for each specific risk factor.**

References:
Hurteau, M. D., Hungate, B. A. & Koch, G. W. Accounting for risk in valuing forest carbon offsets. Carbon Balance Manag. 4, 1 (2009).

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

Badgley, G. et al. California's forest carbon offsets buffer pool is severely undercapitalized. Front. For. Glob. Change 5, 30426 (2022).

Anderegg, W. R. L., Trugman, A. T., Vargas G., G., Wu, C. & Yang, L. Current forest carbon offset buffer pool contributions do not adequately insure against disturbance-driven carbon losses. Glob. Change Biol. 31, e70251 (2025).

Wu, C. et al. Uncertainty in US forest carbon storage potential due to climate risks. Nat. Geosci. 16, 422–429 (2023).

Wu, C. et al. Carbon reversal risks from climate-sensitive disturbances in US forests. In AGU Fall Meeting Abstracts Vol. 2023, GC54D-06 (2023).

Revision 12. Alternative approaches for quantifying certain types of reversals
We believe that the language "avoidable" and "unavoidable" is a better categorization to differentiate reversals, and encourage the Department of Ecology to apply this language, noting that this is the language likely being adopted by the UNFCCC's draft standard for addressing non-permanence/reversals. Such language is important, as there are examples, such as personal or business insolvency leading to the defaulting of an activity participant on their obligations, which illustrate that while a reversal may not have been intentional, it nevertheless is a result of actions by the activity participant for which they are responsible.

Revision 15. Require that projects be developed in line with a Protocol adopted by Ecology in order to receive a DEBs designation
Topic 5. Allow insurance mechanisms in lieu of buffer pool contribution

Buffer pool accounts are far more robust than the insurance products described in the public consultation draft. Insurance policies would need to be required to be held for the entire 100+ year lifetime of a project. Yet, critically, insurance products only insure for a short period of time (e.g. 5-10 years).

In contrast, an adequately capitalized buffer pool could theoretically insure nature-based carbon credits for 50-100 years, which is likely the period of time carbon will need to be stored in such projects to make a real climate mitigation impact depending on emission scenario (Anderegg et al 2025). Instead of allowing insurance products to address durability, the Department of Ecology should better capitalize their buffer pool, based on rigorous, peer-reviewed, independent data sources without a maximum contribution cap to have adequate credits to insure risk of reversal given increasing climate risks.

References:
Anderegg, W.R.L., Blanchard, L., Anderson, C. *et al.* Towards more effective nature-based climate solutions in global forests. *Nature* 643, 1214–1222 (2025). https://doi.org/10.1038/s41586-025-09116-6

Topic 8. Revise 100-year project commitment within the US Forest Protocol
We agree with the Department of Ecology that project time commitments shorter than 100 years for projects that are at risk of reversal are not compatible with the requirements of the cap-and-invest program. The best science suggests that the project commitment period for any project at risk of reversal should be 100 years. This is not only to have a consistent project duration across jurisdictions linked to the program; it is also the scientifically robust choice. Carbon from a project must be sequestered until at least peak warming to have a real climate mitigation impact. The IPCC SSP2-4.5 emissions pathway mapping scenarios with intermediate GHG emissions suggests that peak warming will occur some time after 2100. Therefore, a 100 year durability requirement is a robust and scientifically grounded choice.

References:
IPCC, 2023: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp. doi: 10.59327/IPCC/AR6-9789291691647

Perspective

Towards more effective nature-based climate solutions in global forests

https://doi.org/10.1038/s41586-025-09116-6

Received: 12 July 2024

Accepted: 8 May 2025

Published online: 30 July 2025

Check for updates

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Terrestrial ecosystems could contribute to climate mitigation through nature-based climate solutions (NbCS), which aim to reduce ecosystem greenhouse gas emissions and/or increase ecosystem carbon storage. Forests have the largest potential for NbCS, aligned with broader sustainability benefits, but—unfortunately—a broad body of literature has revealed widespread problems in forest NbCS projects and protocols that undermine the climate mitigation of forest carbon credits and hamper efforts to reach global net zero. Therefore, there is a need to bring better science and policy to improve NbCS climate mitigation outcomes going forward. Here we synthesize challenges to crediting forest NbCS and offer guidance and key next steps to make improvements in the implementation of these strategies immediately and in the near-term. We structure our Perspective around four key components of rigorous forest NbCS, illuminating key science and policy considerations and providing solutions to improve rigour. Finally, we outline a 'contribution approach' to support rigorous forest NbCS that is an alternative funding mechanism that disallows compensation or offsetting claims.

Terrestrial ecosystems play an important role in contributing to climate mitigation, acting as a substantial carbon sink and absorbing an estimated 31% of anthropogenic carbon emissions per year (ref. 1). Ambitious efforts to rapidly reduce fossil fuel emissions remain the most important components of climate mitigation, but there is growing interest in interventions that reduce emissions from and/or increase carbon storage in terrestrial ecosystems through NbCS to supplement and accelerate climate mitigation[2–5]. Of all the proposed NbCS management actions, those implemented in forests have the largest potential for further climate mitigation[2,6]. Given that deforestation at present leads to 1.9 GtC year^{-1} of emissions[1], actions to halt and reverse deforestation are a critical part of climate stabilization pathways[7].

NbCS in forests are increasingly funded by a range of public and private sources[8], using various management actions, including avoided forest conversion/deforestation, reforestation (sometimes combined with afforestation; Supplementary Information Box 1), improved forest management and agroforestry. Substantial interest by the private sector to meet climate commitments has spurred further sources of funding, often channelled towards buying NbCS carbon credits from voluntary and compliance markets[9,10]. Forest NbCS can also provide climate adaptation benefits for local communities, as well as other important co-benefits for people and biodiversity[4,11], but to succeed specifically as 'climate solutions', NbCS must provide rigorous and effective climate mitigation, defined here as emissions reductions and/or carbon removals that decrease global net radiative forcing through global peak warming (Fig. 1).

At present, carbon credits are an important way for private contributors and governments to invest in NbCS and could potentially play a larger role in the future. Unfortunately, a broad body of literature has identified widespread problems with how forest NbCS initiatives through carbon credit markets have accounted for their climate impact[12–26]. Many programmes have issued credits that achieve only a small fraction of what they claim in terms of climate mitigation benefits, which undermines climate progress, particularly when claimed as offsets. Driven by widespread concerns around effectiveness, the present price of carbon credits from tropical forestry NbCS projects fell from a high of more than \$21 per ton CO_2e to around <\$1–2 per ton CO_2e in 2024 (ref. 27). Thus, there is an urgent need to bring better science and policy to bear in directing private and public funds to NbCS that deliver effective climate benefits at scale.

Although several recent publications have developed core principles for improving NbCS quality[5,6,11,15,28–32], we lack a clear vision for doing so at present. Improvements are needed for programme design and for funding mechanisms and the claims made by those buying credits. Here we describe how substantial improvements in NbCS effectiveness and rigour could be made immediately and over the near-term

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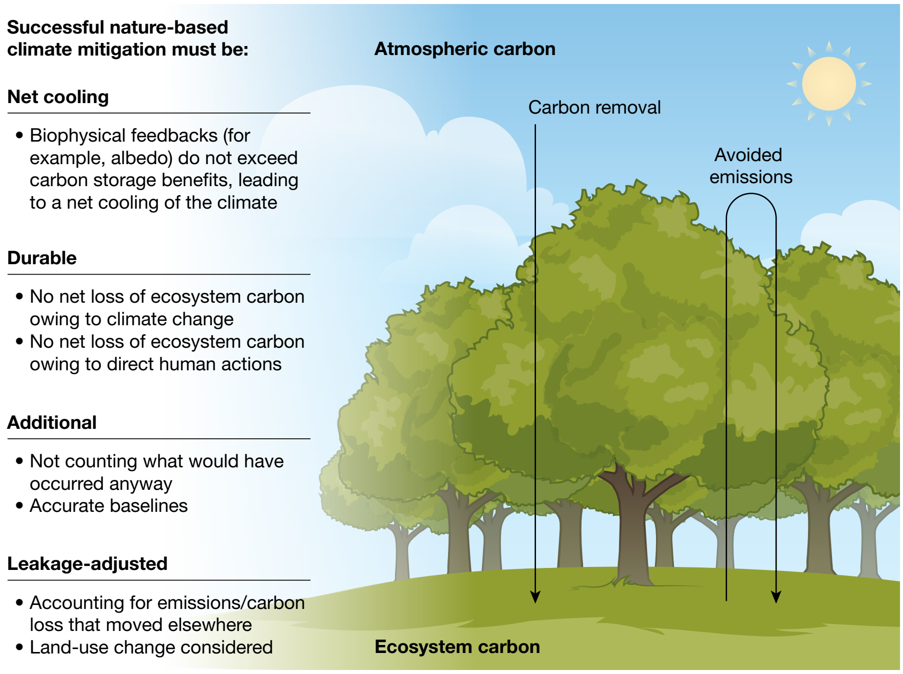

Fig. 1 | Key criteria for effective climate mitigation in forests. Central pathways of avoided emissions and carbon removal and four central criteria for rigorous and effective climate mitigation in NbCS in forests. We note that 'No net loss of ecosystem carbon' under the 'Durable' category means losses beyond what an insurance or compensation mechanism, such as a buffer pool, would cover.

(for example, the next 5 years) (Supplementary Table 1). We first review four critical components (net climate cooling, durability, additionality and leakage) required for NbCS effectiveness and rigour. For each component, we provide an overview of the concepts, problems with present approaches used by carbon crediting methodologies and how better science and data can help address these problems in the near-term (Supplementary Table 1). Finally, we conclude with structural reforms needed to drive rigorous NbCS and illustrate how an alternative to the traditional offsetting approach—a contribution approach—could sidestep many structural challenges in an offsetting framework. We refer readers to Supplementary Information Box 1 for clarification of key terms and concepts.

Four key components of improved NbCS

To succeed with climate mitigation, forest NbCS efforts must satisfy four key components (Fig. 1). Activities must lead to a net global climate cooling by integrating both changes in atmospheric greenhouse gases and biophysical feedbacks, store carbon for a sufficiently long period while accounting for the risk of losses, result in further climate mitigation benefits relative to what would have occurred without the intervention and avoid substantial negative impacts from leakage or the shifting of activities to other parcels of land[5,28]. There are other important social and ethical considerations to take into account, including responsible ecological design, doing no harm to biodiversity or people and respecting community land rights and indigenous communities, which have been covered extensively in other reviews[4,5,11,33]. We focus this Perspective on how to deliver these key scientific components for rigorous and effective forest NbCS climate mitigation.

Net climate cooling

Forests alter climate at local to global levels by modulating water, energy, carbon, volatile organic compounds and aerosols in the atmosphere[34]. These impacts can be loosely binned into 'biogeochemical' and 'biogeophysical' effects, although interactions between the two types of effects occur (Fig. 2). Biogeochemical effects describe how forests influence carbon and nutrient cycles, as well as volatile organic compound emissions, aerosol formation and atmospheric chemistry. Biogeophysical impacts capture how forests mediate water and energy exchanges between the land and atmosphere.

Albedo is an important biogeophysical effect and exerts first-order control on the net surface radiative balance of the Earth system. Forests tend to have lower albedo than other land surfaces[34–36] and absorb a larger fraction of incident solar radiation, warming the climate. Thus, persistent changes in forest cover—both losses and gains—will change albedo and will affect the climate mitigation benefit of both avoided forest conversion and reforestation initiatives[35–38]. Some landscapes are particularly reflective—such as places with persistent snowpack, bright soils or grasslands. In these landscapes, trees can substantially reduce albedo. The relative importance of albedo depends on carbon storage within the forests. In places in which carbon storage is high and albedo change is low, accounting for albedo will not substantially alter climate mitigation estimates of a project. But there are places in which the reduction of albedo can outweigh the carbon storage within the system, such as boreal forests or semi-arid drylands with sparse vegetation[38,39]. Quantifying this albedo change is thus essential for understanding where forest projects might provide a net climate benefit.

For improved forest management, the degree to which albedo is a concern remains uncertain but is probably small. The relationship between stand age and albedo tends to be nonlinear and saturating[37,40,41]. As a result, activities that maintain forest cover for longer periods of time (for example, extended rotations) may not result in substantial changes to albedo, but quantification of the albedo impacts of most improved forest management practices is scarce[37].

Solutions and research needs

Despite the potential for albedo to reduce or even negate the climate mitigation benefits of avoided conversion and reforestation, it is not considered in any carbon crediting protocols so far. Fortunately, albedo is readily measured by many remote-sensing platforms, and datasets that transform albedo changes into information relevant for carbon

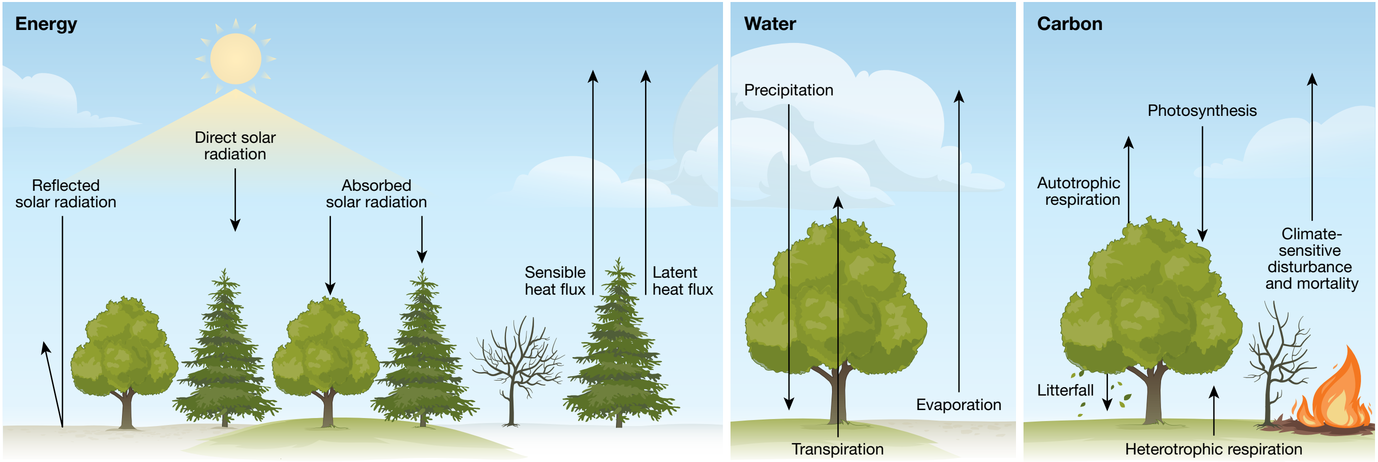

Fig. 2 | Key fluxes that mediate climate benefits of forests. Illustration of multiple key land–atmosphere interactions that mediate net climate impacts in energy, water and carbon cycles. Additional relevant feedbacks around clouds and circulation are not shown here.

accounting now exist[36,38,42]. Moving forward, albedo would ideally be incorporated in climate mitigation quantification of NbCS in two prominent ways (Supplementary Table 1). First, carbon projects should not be allowed in places in which warming induced by lowered albedo outweighs the carbon storage benefit[38]. A second method for accounting for albedo change would be to fractionally reduce the expected climate mitigation benefit (for example, credits) from individual projects based on the expected changes in albedo. More detailed sampling of albedos for a range of land cover, land management and land-use conditions in unique geographies is needed to improve rigour and accuracy. More robust consideration of effective radiative forcing (after dynamic Earth system adjustments) and its efficacy (the spatiotemporal patterning of its magnitude) relative to well-mixed, long-lived greenhouse gases is also important.

Key near-term future research needs include improved understanding, models and maps of the impacts of cloud feedbacks, volatile organic compounds and aerosol effects on climate[43]. Research is needed to distinguish the direction and relative importance of different feedbacks (surface albedo, volatile organic compounds and aerosols and clouds) at local and global scales (Supplementary Information). Finally, although a single project in isolation is unlikely to cause large changes in cloud cover and other hydrologic cycle feedbacks, implementing forest NbCS at large scales (such as jurisdictional REDD+ initiatives) is likely to cause substantial changes in cloud cover that may accentuate or reduce changes in surface albedo[44]. Therefore, such hydrologic cycle feedbacks should be quantified and considered in albedo accounting at regional scales.

Durability

The durability of carbon storage refers to the length of time over which carbon remains outside the atmosphere. Forests face increasing disturbance risks that can drive carbon losses and compromise durability[13,15,45], such as wildfire, drought, biotic agents (pests and pathogens), wind events, severe storms, sea-level rise and invasive species[45]. Forests frequently regrow after these disturbances—but not always[46,47]. Thus, the most critical disturbance risks for NbCS initiatives are those that are climate-sensitive, widespread, severe and increasing, leading to lower regional carbon stocks over decades[15]. Also, forests face a wide range of socio-economic risks that can lead to their conversion to other land uses and/or prevent reforestation.

The dynamics of CO_2 emissions to the atmosphere have important implications for the climate mitigation value of NbCS and, in particular, the durability outcomes needed to realize different climate mitigation benefits. On societally relevant timescales, owing to the long-lived nature of CO_2, burning fossil fuels causes an effectively permanent change to atmospheric CO_2 concentrations[48,49]. As a result, long-term global mean temperature outcomes are expected to be driven by cumulative CO_2 emissions, rather than the timing of those emissions[50–55]. To reduce peak global temperature, carbon must be stored outside the atmosphere for at least as long as it takes to reach global peak temperature (50–100+ years, depending on the emission scenario) and only as a complement rather than a substitute for rapid fossil fuel emissions reductions[56,57].

The durability of carbon storage needs to match the claim being made for a given NbCS intervention or carbon credit[55,58]. Many carbon crediting programmes today equate the climate mitigation value of forest NbCS with the effectively permanent damages from fossil CO_2 emissions[59]. Durability commitments—the period of time over which a project or programme commits to preserve and monitor credited carbon—in carbon credit protocols are not permanent and usually in the range 1–100 years (refs. 18,19,60). Most forest carbon credits issued so far have been under protocols with a minimum project lifetime of 20 years (Supplementary Table 2). Thus, in physical terms, nearly all real-world durability commitments are incommensurate with the climate impacts from CO_2 emissions.

The most common durability risk-management tool is called a buffer pool. To construct a buffer pool, the programme administrator establishes guidelines for assessing the risk of reversal (that is, carbon loss) from natural and social/economic factors across the durability commitment period and then projects set aside a percentage of the carbon credits based on the level of anticipated risk[16]. When there is a qualified reversal in the carbon crediting programme, the programme administrator retires carbon credits from the buffer pool equal to the calculated net carbon losses. The buffer pool of a programme functions like an insurance programme and is designed to compensate for unintended reversals of carbon credits over the durability commitments of enrolled projects.

Several studies have found that present buffer pools are probably inadequate[13,15,16,61]. Across all protocols and credits issued up to December 2023, the credit-weighted average buffer pool size was 13.7% of credits issued and the most common value was about 12% (Supplementary Fig. 1). By contrast, Haya et al. (2023) found that about 26% was probably a conservative floor for stand-clearing disturbance and timber harvest disturbances in REDD+ projects. Wu et al. (2023) observed that roughly 36% of area in California's compliance offset projects was projected to lose carbon over the twenty-first century in a mid-range emissions scenario.

Solutions and research needs

The buffer pool contributions used by considerable forest NbCS efforts are not at present based on current, rigorous science and need to be revised[15,16,19] (Supplementary Table 1). More rigorous disturbance and reversal data are now available and should be directly incorporated into policies and protocols immediately by updating buffer pool contributions[16,61–63] (Supplementary Information). Disturbance return intervals can be estimated from historical data and combined with simple demographic models to estimate carbon trajectories over 100-year periods[64], although this approach does not directly include future climate change impacts. Detailed integrated 100-year reversal risk estimates and buffer pool contributions are forthcoming for US forests and early estimates for global forests as well[62]. Instead of the present piecemeal approach, it would be more robust and consistent to use a spatially explicit durability risk map based on the latest science and developed by independent scientists.

Key data gaps for assessing durability risk include independent, open-source tools based on peer-reviewed studies that provide consistent and spatially explicit risk maps and buffer pool sizes for each disturbance type that include projected trends in occurrence and severity owing to climate change, higher specificity or granularity for the risks by species, forest and/or project type, revised data-constrained estimates of the social risks to forest projects and more research and syntheses on which management actions can meaningfully influence disturbance risk in specific biomes and regions. Considering the enormous uncertainty in natural and social durability risks, we recommend conservative buffer pool allocations that protect against more extreme scenarios. Finally, given the present uncertainty about how effectively and under what conditions management interventions can reduce natural reversal risks, we further suggest that any deductions to buffer pool contributions based on management interventions be minimal or zero unless risk-specific science is available. Projects could be rewarded post hoc if management actions reduced risks relative to previous expectations. This approach would be conservative with respect to the net climate mitigation benefits achieved by NbCS projects[65,66].

Additionality

Additionality addresses whether the NbCS activity leads to further climate benefit compared with what would have happened without the climate investment[67]. Because additionality depends on effectively estimating an alternative outcome (that is, a baseline counterfactual of what would have occurred without the NbCS investment), it can involve marked uncertainty[68] and, so far, has been the source of a substantial portion of overcrediting from NbCS carbon crediting protocols[19,20,22,23].

The challenges of appropriately determining baselines and additionality differ by project category. Additionality in reforestation/afforestation projects requires action—for example, tree planting or supported natural regeneration—beyond what would have occurred without the climate finance. Although additionality and baseline concerns are generally perceived to be lower with reforestation projects compared with avoided conversion or improved forest management, they still apply. Uncertainty remains around natural recovery, land-use change (for example, would previous land uses have continued or changed without the NbCS) and whether reforestation would have happened without the climate finance. For avoided conversion and improved forest management, which involve changes in practice over time rather than a particular action such as planting trees, additionality is largely defined as a change from the baseline. Avoided conversion baselines hinge on predictions of forest loss without the NbCS investment[22,69]. Additionality in improved forest management projects depends on projects changing land management practices as a result of NbCS investment (for example, NbCS funding led to extended timber harvest intervals or reduced impact logging)[19]. In practice, additionality and baseline requirements are handled in a variety of ways, but present tools have generally been inaccurate owing to uncertainty in true baselines and flexibility given to project developers' selection of baseline scenarios[17–19,70,71].

A broad body of recent peer-reviewed literature using post hoc evaluations has documented inaccurate and inflated additionality claims in projects across the world[17,20,23,24,26,70,72–74]. For example, several research papers on California's compliance improved forest management offset protocols have documented extensive overcrediting and little or no evidence of additionality across projects in the USA[17,20,23,24]. For a subset of 16 substantial tropical REDD+ avoided conversion projects, a recent large study estimated that only about 6% of estimated credits were probably additional and that inaccurate historic baselines of deforestation rates drove this notable overcrediting[22]. An extensive analysis of 182 reforestation projects in Australia's carbon offset scheme found little evidence of additionality, as project areas largely mirrored non-project areas[26].

Solutions and research needs

A range of recommendations have been made recently for improving additionality and baseline assessments for improved forest management[19], reforestation/afforestation[26] and avoided conversion/REDD+ (ref. 70) projects. Here we discuss two main trends in baseline setting for forest projects that could improve additionality if done well (Supplementary Table 1).

First, a move towards dynamic baselines should, in theory, improve additionality. Dynamic baselines involve matching project sites with control sites that are theoretically identical except for the project activity. The additionality within the project site is then evaluated relative to the control sites, rather than a historical counterfactual. Dynamic baseline methods are considered best practice for research assessing the performance of a forest programme or intervention[70] and are still fairly new in carbon crediting programmes, although their use is growing (Supplementary Information).

The value of dynamic baselines, however, will hinge on the appropriateness of the control sites, which hinges on the robustness of data sources within both the project and control sites. Dynamic baselines only make sense for project-level interventions in which appropriate control sites (for example, synthetic controls) are available. Advances in remote-sensing data and modern ground-based measurements to map carbon stocks and fluxes continuously over time (that is, annually) at relevant spatial scales will improve identification of appropriate control sites and dynamic baseline estimates[28,75,76]. Ultimately, full transparency of selection processes, algorithms, remote-sensing data quality and control plots will enable independent evaluation of the appropriateness of the comparison. Improved maps of past and present management practices, including timber harvest return intervals, location and type of agroforestry practices, will help improve rigour. Moreover, maps of management practices in the grasslands and agricultural lands are needed, as these are the baselines in most reforestation and avoided deforestation projects.

Second, there is growing interest in supporting avoided deforestation efforts at the jurisdictional level—across an entire country, state or province—rather than at individual parcels. Proponents argue that jurisdictional programmes can better account for leakage and reduce the potential for adverse selection[77,78]. Although well-designed jurisdictional programmes can be more effective than a mosaic of individual projects, jurisdictional baselines remain subject to marked uncertainty[79] that cannot be mitigated with dynamic baselines owing to the lack of appropriate controls. Many jurisdictional programmes, including ART TREES, set baselines using historical deforestation rates. Because these rates can change greatly from year to year in response to changes in global commodity prices and policies in other countries[80,81], the choice of benchmark historical rates is uncertain and any fixed approach could lead to adverse selection[82–84]. Also, accurate evaluation of programme effectiveness needs assessments of how well programmes address the drivers of deforestation in the particular jurisdiction. Historical baselines can also be inaccurate as applied to countries with stochastic trends in deforestation rates, including those with low historical deforestation rates that may face higher deforestation in the future[85]. And although jurisdictional programmes better address domestic leakage, none of the methodologies used today accounts for international leakage effects, such as market-mediated effects on commodity prices[18,86,87].

Leakage

Leakage occurs when an NbCS activity causes a shift in activity between the project area and another area outside the project area, which reduces or increases the net effect of the intended intervention. Two general types of leakage are considered in the literature: activity leakage (sometimes termed 'activity shifting leakage') and market leakage. Activity leakage occurs when a specific activity being reduced by an NbCS project (for example, deforestation) moves to another area. Market leakage occurs when an NbCS activity changes market conditions, for example, by reducing supply of timber in one region, which creates incentives for increasing timber supply elsewhere. Activity leakage can potentially be monitored directly, whereas market leakage cannot be monitored at the project level and instead must be estimated with economic modelling[88]. With market leakage, information is often transmitted through price. In interconnected markets, the results of outputs by various producers of different products are complex.

Activity leakage can theoretically be tracked by monitoring changes in deforestation or timber harvest rates with satellite imagery in a pre-established leakage zone around the project area[18]. Present NbCS methodologies estimate market leakage at the beginning of the project and typically apply the rate throughout the course of the project. Some, but not all, REDD+ methodologies estimate market leakage. In REDD+ methodologies that do estimate market leakage, only domestic market leakage is assessed and deducted, and international leakage is ignored, despite international leakage being known to occur with forest commodities[18].

Methodologies apply a leakage deduction to adjust the amount of credits issued to a project. Leakage deductions applied by Verra REDD+ projects are typically slightly low: 2.6% for activity leakage and 4.4% for market leakage[18]. The scientific literature suggests that market leakage varies between 10% and 70% for REDD+ projects and a meta-analysis found an average of approximately 40% carbon leakage across studies in the forest sector[18]. This suggests that projects generating credits under present market-based NbCS protocols are probably substantially underestimating leakage effects[18,88,89].

Solutions and research needs

Project developers should have less flexibility to define leakage zones and estimate baseline deforestation rates within it (Supplementary Table 1). Protocols should require a market leakage deduction when a project involves reduced production of a commodity. International market leakage should be accounted for and leakage rates should conservatively reflect rates documented in the literature based on independent datasets and tools. Market leakage should be deducted around the same time as the production is assumed to be reduced to avoid substantial overcrediting[19].

Distinguishing the drivers of natural and anthropogenic forest loss over a region, particularly at project-relevant scales, is a crucial research need[90,91]. Such datasets could be used to track whether anthropogenic drivers of forest loss increase in rate in areas beyond project boundaries as a result of the project. These rates should be characterized at relatively high spatial resolution (that is, 30 m) over time (for example, decades) before the establishment of a project to identify leakage as a period of increased forest loss relative to the typical background rates of loss. A combination of forest economic models and remotely sensed patterns of land management, timber harvest and deforestation could potentially be used to provide better data constraints on leakage. Models will probably need to capture the drivers of land-use change or forest management in a given region, be extensively validated on independent datasets to ensure confidence on projections over future decades and provide a detailed characterization of uncertainty.

Finally, given enormous uncertainty in leakage estimates at present and challenges in robustly estimating leakage rates in the near-term, protocols should focus on projects (types, regions and characteristics) for which there is greater confidence that the benefits are unlikely to be undone by leakage (Supplementary Information). Such projects increase carbon storage or reduce carbon storage loss with little decrease in production or usable land or are paired with activities that reduce leakage pressure (for example, pairing avoided conversion projects around urban areas with policies that increase urban density).

NbCS programme structural reforms

As well as the crucial scientific reforms needed for rigorous forest NbCS described above, structural reforms that affect both the supply and demand sides of NbCS initiatives are urgently needed. Voluntary reporting standards have required separate reporting of an organization's direct emissions and purchased carbon credits, but public disclosure is still limited, although requirements are coming in some jurisdictions[10,92,93]. To enable independent analysis of the effectiveness of corporate climate action and increase confidence, the location and nature of NbCS interventions used as offsets—as well as all information that an external analyst would need to independently recalculate the benefits and understand the source of data and assumptions—should be publicly available (Supplementary Information), as is now required for carbon credits under California's new law, AB-1305 (ref. 93).

Better transparency in methodology and measurements of NbCS projects and activities will also be crucial to developing rigour in NbCS initiatives. Although required transparent data will probably vary depending on the activity and protocol, we suggest that a minimum floor of required data for NbCS projects and initiatives include the digital geospatial data that accurately define geographic boundaries of the interventions, either the proposed intervention activities and how those depart from the previous 20+ years of land management for projects using a historical baseline or selected control plots/regions for projects using a dynamic baseline, carbon crediting modelling/graphs that clearly show the assumed baseline for each individual project, and how that baseline was calculated, and forest composition of the intervention area at the initiation of the project necessary for independent reproduction of crediting and baseline scenarios. Funding for the creation and maintenance of these transparent, open and easily usable datasets is important and could be game-changing if provided by public and/or philanthropic sources.

Structural independence of NbCS project verifiers is a crucial design change needed to remove potential or perceived conflicts of interest. Instead of the present structure of credit-producing programmes in which verifiers are hired by project developers, verifiers should be hired by programme administrators or separate independent parties[94]. Alternatively, verifiers could be required to be chosen randomly from a common pool, hired from pooled resources and rewarded for accuracy[95].

The contribution approach to NbCS

There are several reasons why considering an alternative approach to NbCS may be valuable. Existing NbCS carbon credits have marked challenges with quality, as discussed above, making it legally and reputationally risky for corporations and other buyers to make emission reduction claims using many of those credits[96]. Corporations increasingly face legal complaints and greenwashing accusations for making offsetting-related claims that are considered misleading or unsubstantiated, which can violate consumer laws[97,98].

Conventional offsetting is based on a ton-for-ton model, in which a person or company buys an equal number of carbon credits as the emissions they seek to 'offset'. This approach can drive demand for high-volume, low-cost carbon credits[99], which can have benefits by encouraging economies of scale, innovation and renewed investment, but also at present probably have less real climate mitigation impact[100]. The present offsetting approach has structural incentives built into it such that many actors involved in producing carbon credits benefit from inflated estimates of project climate benefit[18,32,101]. Thus, it remains an open question whether the existing system can be meaningfully reformed to deliver rigour and effectiveness in the next 5–10 years.

Opportunities in a contribution approach

The contribution approach is an alternative framework for corporations and other organizations to support NbCS without claiming the resulting emissions reductions or removals offset or neutralize their own greenhouse gas emissions[102]. Under a contribution approach, instead of using carbon credits to report lower net emissions, a buyer would claim that they have only made a financial contribution to global climate mitigation. The largest incentives for companies and other organizations to buy into a contribution approach are that contribution claims are more scientifically accurate, straightforward and legally defensible, reducing legal and reputational risks. Also, the alternative funding models in a contribution approach can help channel the financial resources of an organization to potentially more strategic and high-impact efforts to reduce emissions inside and outside traditional carbon markets.

A contribution claim can be more scientifically accurate and legally defensible than a conventional offsetting claim because it does not presume equivalence between the climate mitigation benefits of NbCS with the harms of greenhouse gas emissions. Given the difficulty of precisely quantifying NbCS interventions and the incommensurability of the CO_2 temporarily sequestered within NbCS to fossil fuel emissions[55,103], this approach allows stakeholders to recognize the climate and co-benefits of NbCS without claiming equivalence of emissions reductions.

Although contribution claims cannot support statements that companies have achieved carbon neutrality or net zero, companies might nevertheless consider a shift from offsetting to contribution claims to reduce legal and reputational risks. Consumer protection and false advertising laws prohibit false or misleading statements, which could present legal risks if a company relies on low-quality carbon credits to substantiate a carbon-neutrality or net-zero marketing claim. By contrast, contribution claims may be more responsive to, and present fewer compliance risks under, existing and emerging regulatory measures. For example, the European Parliament's recent revision to its Unfair Commercial Practices Directive[104] prohibits conventional offsetting claims for consumer products and suggests that contribution-type claims may be appropriate.

The contribution approach is compatible with many beyond value chain mitigation (BVCM) guidelines[105–107]. BVCM guidelines help corporations more credibly set science-based targets and engage with BVCM activities in a more transparent manner. These guidelines typically include recommendations that companies assign priority to direct emissions reductions, raise funds through ton-per-ton, money-per ton or money-per-money models, assign priority to the spending of such funds on effective climate mitigation and transparently making contribution and other more accurate claims.

When companies follow such BVCM guidelines, the contribution approach offers several potential advantages for advancing rigorous NbCS. The first advantage is that it facilitates fundraising strategies that could drive demand for higher quality NbCS, specifically by disconnecting demand for NbCS from a ton-for-ton compensation model. Alternatively, companies could use a money-per-ton approach in which they set an internal carbon fee (or tax) on their own emissions to encourage reductions and use fee revenues to fund NbCS or other BVCM approaches. BVCM guidelines recommend an internal carbon fee be set at the social cost of carbon, generally considered to be \$100 to >\$283 per ton[108–111] and higher in wealthy regions if equity weighting is used[112]. Alternatively, under a money-per-money fundraising approach, a corporation would commit a percentage of its annual profits or revenues to support rigorous NbCS. Both of these alternative fundraising approaches could change the incentive structure of demand for carbon credits to allow corporations to focus their set budget on high-quality climate mitigation initiatives. This could potentially create a 'race to the top' for high-quality NbCS initiatives both inside and outside carbon markets, rather than the present incentive for quantity. It also provides flexibility to channel financial resources to a wider pool of critical investments, for example, towards efforts that broadly decarbonize economic sectors and/or protect natural resources through system change, including advocacy for stronger climate and forest protection policies.

A second advantage of the contribution approach is that, if buyers shifted their focus to high-quality NbCS initiatives, project developers may have less incentive to inflate an initiative's climate benefit and more incentive to rigorously quantify it. Thus, project developers could be more open to the structural shift in third-party certification described above[32]. Such an incentive structure could also promote the development of, and demand for, NbCS quantification methods by independent analysts without conflicts of interest.

A third advantage is that the contribution approach allows entities to fund NbCS while quality issues and uncertainty around NbCS carbon credits remain. This is especially useful if revisions to incorporate the rigour outlined in this synthesis are delayed or not fully implemented in NbCS carbon crediting protocols. One example of contribution approaches already driving companies to financially support potentially high-quality initiatives as an advanced market commitment is the 'Frontier' initiative focused on accelerating the development of durable carbon-removal technologies.

Critics may argue that corporations might stop investing in NbCS if they can no longer make offsetting claims. However, research shows that corporations engage in carbon markets for reasons beyond reaching emission reduction targets[96,113]. Corporations also engage in carbon markets for market competitiveness (for example, as a branding tool) and to uphold and embody corporate values (for example, supporting the Sustainable Development Goals and to do their part for climate mitigation). In a recent study, about 31% of companies listed market competitiveness and about 32% listed corporate values as reasons for purchasing carbon credits[113]. These findings illustrate that, although some corporations may want to maintain an offset-claiming approach, many corporations already buy carbon credits for reasons that can be aligned with a contribution approach. Furthermore, it is not clear that consumers are swayed towards offsetting claims more than other types of claim. Rather, research indicates that public comprehension of green claim terminology—including climate claims—is low, even among the most environmentally engaged consumers[114,115]. This suggests that corporations can differentiate themselves from their competitors, potentially with more flexibility to tailor to their interests and values, and that consumers may not be strongly swayed one way or another between the advertising of a corporation making an offsetting versus contribution claim.

Another common concern is that the contribution approach could allow corporations to focus on charismatic (for example, compelling narratives around social or biodiversity benefits) projects with limited climate benefit. This is indeed an open question. In this scenario, the cost of funding the charismatic project itself is that the corporation's money has been spent less effectively on climate mitigation than it could otherwise have been. This is arguably better for the climate than when companies use ineffective carbon credits in lieu of real emissions reductions, which results in an increase in greenhouse gases in the atmosphere and climate damages[26]. Such risk can also be mitigated as third-party watchdogs, including civil society organizations, academic researchers and institutions, journalists and private sector ratings agencies, continue to examine the impacts of corporate climate funding[116].

Relatedly, a risk of the contribution approach is the decoupling of a corporation's residual emissions from support for climate mitigation elsewhere when the money-per-money fundraising pathway is chosen. This could potentially decrease the amount of funding channelled towards NbCS initiatives, at least initially. However, if rigorously identified and quantified NbCS initiatives were strategically funded, the real climate-mitigation impact-per-dollar would probably go up. Best practices recommend that the money-per-ton fundraising pathway should be used by high-profit companies, whereas the money-per-money pathway could be useful for the small percentage of heavy-emitting companies (for example, utilities, air travel, cement) that generate profits of less than \$100 per tCO_2 of emissions[117]. An estimated US\$27 billion per year could be generated if just 141 high-profit companies spent \$100 per ton they emit, representing a small percentage of their profits[117].

Contribution approaches are gathering interest around the world. Contribution claims are considered within the UNFCCC's Paris Agreement in both Article 6.4 as 'mitigation contribution units' and in Article 6.8 as 'non-market contributions'. In the voluntary context, the contribution approach is already being promoted and implemented by companies (for example, Klarna, Ocean Outdoor and United Airlines), climate finance project curators (for example, Milkywire and Pinwheel) and registries (for example, the Gold Standard). For the approach to be implemented more broadly, more demand for the approach could be generated if corporate climate standards required contribution claims. Also, third-party accreditation would help mainstream the approach. Nevertheless, the contribution approach is an increasingly promoted option for corporations and others interested in investing in BVCM in a more credible way and could contribute impactful, needed funding to rigorous NbCS.

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Acknowledgements This article is the product of the Wilkes Center for Climate Science and Policy at the University of Utah's Working Group on Rigorous Nature-based Climate

Solutions in Forests. We thank S. Cook-Patton, who was a co-author on the initial manuscript and contributed to idea generation, writing and revisions, but is not listed in the final draft owing to differences in opinions about final recommendations. We thank K. Riley and P. Ellis for providing feedback on this work. W.R.L.A. acknowledges support from US National Science Foundation grants 2003017, 2044937 and 2330582 and Alan T. Waterman Award IOS-2325700.

Author contributions W.R.L.A. and L.B. wrote the first draft of the manuscript. W.R.L.A., L.B., C.A., G.B., D.C., P.G., M.L.G., B.H., J.A.H., M.D.H., M. Lague, M. Liu, K.A.N., J.R., A.T.T., J.A.W., C.A.W., C.W. and L.Y. contributed to idea generation, literature synthesis, writing of several drafts and revisions.

Competing interests D.C. previously consulted for Isometric and is a member of the Milkywire Climate Transformation Fund Advisory Board, the UNFCCC Article 6.4 Mechanism Methodological Expert Panel and California's Independent Emissions Market Advisory Committee. The other authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-025-09116-6.

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Peer review information *Nature* thanks Jiehong Lou and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Towards more effective nature-based climate solutions in global forests

Supporting Information

Next Steps on Net Climate Impacts

We foresee two prominent ways that albedo could be incorporated into NbCS policies and protocols. These changes would be most important to incorporate into reforestation/afforestation protocols where a recent global analysis was published that enables direct quantification of albedo's impact[1]. First, voluntary carbon registries and compliance market bodies should revise protocols to use the 'albedo offset' map in Hasler et al. (2024)[1] to disallow afforestation or reforestation project development in grid cells where the radiative forcing impact from the change in albedo exceeds the radiative forcing benefit from carbon storage in a forest project. The 'albedo offset' map provides the fractional climate impact (radiative forcing) that albedo change would 'cancel out' from the carbon storage benefit of a given project. For example, a 50% albedo offset indicates that albedo change roughly negates around 50% of the climate mitigation benefit from carbon storage in a given grid cell. This exclusion threshold provides a very clear and straight-forward map of where the net climate impact of reforestation/afforestation is likely to be warming and thus should be avoided for programs with climate mitigation goals. We note that it might be useful to exclude projects that exceed a certain threshold of albedo offset lower than the 100% threshold (net warming) – a tiered approach – with the goal of conservative crediting, but this is a normative decision[2].

Second, voluntary carbon registries and compliance market bodies should revise protocols to fractionally reduce the credits issued using the 'albedo offset' map in Hasler et al.

(2024), in a similar manner to the current leakage deduction. Protocols could require carbon projects to upload a geographic project boundary or centroid point to the open-source tool from Hasler et al. (2024), extract the albedo offset for that project, and then adjust the crediting calculation by deducting the albedo offset fraction. Furthermore, projects could monitor albedo change with in situ or remote sensing measurements within the project boundary and update the albedo deduction dynamically with more granular, local data that would better account for specific project species composition, density, soil albedo, etc.

Concerning key near-term future research needs to improve the incorporation of cloud feedbacks, volatile organic compounds, and aerosol net climate impacts of NbCS projects[3–5], we believe a coordinated set of modeling experiments is needed to advance these areas to provide implementation-ready tools. In particular, a comprehensive series of model experiments that would generate Green's Function across a range of climate models (similar to those produced for sea surface temperatures[6,7]) to characterize climate response to local-to-regional scale changes in albedo evapotranspiration, VOCs, and aerosol emissions, individually, would be a critical step to moving beyond the radiative kernel approach from albedo[1]. This would capture not only the instantaneous local radiative effect of a change in land albedo, but also the change in planetary albedo (impacted by clouds and other processes) that is critically necessary for global (not just local) temperatures. Such Green's Functions could also be produced for other key surface properties (e.g. relating to aerodynamics and evaporation). The key difference between a radiative kernel versus a Green's Function is that the radiative kernel provides the instantaneous radiative effect of a given change (e.g. in land surface albedo at one location), without any adjustments or feedbacks to that change, while a Green's Function quantifies the full system response to a given change (e.g. a change in land surface albedo at one location), which is composed of the direct instantaneous effect and all the responses and feedbacks within the system[8].

Kernels are generated by running the radiative transfer code of a model offline at each timestep, once with no change (these are the fluxes passed to the model to integrate forwards) and once with the imposed change (e.g. in surface albedo; these fluxes are saved to the kernel, but are not passed to the model for the next time step – the model is unaware any change was made to surface albedo). In contrast, a Green's Function has a change imposed on it that impacts the forward integration of the model – the change in albedo alters surface and top-of-atmosphere (TOA) fluxes which alter atmospheric processes which potentially feedback on surface and TOA fluxes[8].

In the Green's Function experiment, a substantial amount of the net surface and net TOA radiative fluxes are mediated by atmospheric feedbacks to the surface change. In the radiative kernel, there are, by design, no feedbacks. The Green's Function approach has an additional benefit of not being restricted to local effects - it could capture changes in circulation. The radiative kernel can only capture the direct effect on the local column radiation balance.

Because a radiative kernel doesn't need to propagate information from imposed perturbations in either space or time, one can generate a kernel with one coupled model run. In contrast, a Green’s Function approach requires running a fully coupled land-atmosphere simulation for each location one is interested in perturbing. This likely makes it impractical to run for a given NbCS project, but could theoretically be run for a substantial forest cover change within a jurisdiction. Thus, a suite of model experiments that developed Green’s Functions for a range of NbCS jurisdictions across a range of climate models could provide a quantitative key basis of these additional feedbacks on radiative forcing and maps that could be incorporated into protocols similar to the approach described with albedo above, although uncertainties in constraining net TOA fluxes from satellites may be a barrier[9].

Next Steps on Durability

The immediate next steps to update buffer pools with the best-available science involve voluntary carbon registries and compliance market bodies updating protocols to require that buffer pool sizes and contributions be calculated from an independent, third-party dataset that provides rigorous buffer pool calculations that include climate change trends[10,11]. Similar to albedo, project developers would use an easily-accessible web tool to upload a geographic boundary file or centroid coordinate of the project and receive a buffer pool contribution set of scores. This initial tool provides disturbance-specific buffer pool sizes for wildfire, drought, and insect outbreaks in the United States and a single combined 'stand-replacing' disturbance score for forests globally. This tool can and should be updated to include additional granularity of other disturbances, such as wind and storm disturbances, and disturbance severity at jurisdiction and global scales. We note that there is substantial complexity, which is beyond the scope of this review paper to cover, around how buffer pools are capitalized and tapped by reversals that vary by protocol that must be carefully addressed in protocol updates[12].

Next Steps on Additionality and Baselines

The two approaches we highlight as potentially promising for baseline assessment that avoids overcrediting—dynamic baselines and jurisdictional approaches—are just starting to be used to generate carbon credits and so ongoing research on their effectiveness is needed to refine them over time, and to assess if they are able to reasonably avoid significant overcrediting. This analysis should be performed by independent researchers (i.e. without interest in the outcomes) either on their own or under contract by program administrators. Transparency is necessary to enable external analysis, and involves providing all the information needed for external analysts to assess data sources and assumptions, and to reproduce the baseline calculations, as required in California bill AB 1305 and as is standard for academic articles. Further, program administrators should nimbly improve methodologies as understanding improves. A shift to a contributions approach facilitates this process of analysis and improvement by reducing the legal risk associated with discovering that previous scientific understanding resulted in excess crediting.

Core datasets for estimation of dynamic and jurisdictional baselines include time-series calculations of carbon stocks (e.g. aboveground live carbon) from forest inventory plots and/or from rigorously-validated remote-sensing products, time-series maps of land use (e.g. agriculture, forest), and time-series maps of land management (e.g. timber harvest, forest degradation). Other ancillary data around climate, forest type, soil, distance to road, and land ownership data will also likely be important for dynamic baselines[13,14]. These remote-sensing products will likely need to be at high enough resolution to detect project-level changes and establish robust comparison control pixels to project pixels.

Dynamic baselines are considered best practice for baselines in the context of many similar activities and actors. Adverse selection remains a risk with dynamic baselines since methods for establishing control plots cannot capture all factors that affect what would have happened without the carbon finance[15].Other baseline-setting methods are needed for certain locations or landowner types where dynamic baselines are not viable[16]. For these, more research is needed to determine effective baseline setting methods.

Dynamic baselines can also account for additionality when baselines are an effective measure of additionality. Additionality and baselines are different assessments when projects involve a discrete action, like restoring a degraded forest, rather than a change in forest management over time such as extended rotations. For these projects, dynamic baselines can assess the baseline, but a separate additionality assessment is also needed. Additionality assessments involve understanding of the specific location and factors affecting decisions in that context which should be performed by independent analysts with contextual knowledge on a project category or individual project basis.

On jurisdictional REDD+, in addition to the datasets described above, multi-method case study analyses of specific programs will be important to explore how effectively programs address deforestation drivers and how criteria can be improved for determining which jurisdictional programs meet basic quality criteria. Effectiveness criteria includes how well programs address deforestation drivers, fairly engage with forest-dwelling communities in program design and implementation, and set accurate and conservative baselines.

Until we have more experience with these new baseline methods and they have been demonstrated to be reasonably accurate, baseline setting should lean heavily towards conservativeness to avoid the previously-observed pervasive overcrediting.

Next Steps on Leakage

Concerning flexibility in leakage zones, leakage zone calculations could be required to use an independent, third-party tool similar to the approach proposed here for buffer pool contributions for durability. Furthermore, prescribed minimum floors of activity leakage could at least partially address the challenges around flexibility.

Leakage mitigation can take many forms. For REDD+, leakage mitigation activities can involve addressing underlying drivers of deforestation, including by engaging local communities in program design, and coordinating across broader geographical scales to manage land use changes comprehensively[17,18]. In general, when an NbCS project results in a reduction in production (e.g., timber or agriculture), mitigation activities can increase production in ways that do not lead to further loss of forest carbon, such as pairing extended rotation projects with forest restoration activities that include thinning, and forest protection with agricultural intensification. The outcomes of these mitigation activities should be monitored and conservatively quantified and leakage deductions should be made for the portion of leakage not made up by mitigation activities. More rigorous quantification of the effectiveness of some of these activities could involve periodic re-assessment of activity leakage rates with remote sensing data[19].

Models can help illuminate how the expected magnitude of leakage varies by region, project type, market, and policy coverage. Higher leakage rates are expected where policy coverage is narrow (e.g. smaller geographic scales), smaller scales of activity displacement, more connected or integrated markets, higher producer flexibility in the market, availability of proximal alternative lands for production, and higher carbon emissions from the leakage zones than the project areas[18,20]. Policy coverage and scales of activity displacement are generally known at a protocol-level via what regions are in scope and how many projects have been developed or proposed to date. Market connectivity and producer flexibility are more challenging to estimate but a range of social science and econometric methods can provide insights and constraints. The availability of relevant nearby alternative lands and carbon emissions from the leakage zones can partially be estimated with remote-sensing data to track similar lands to proposed projects and carbon losses from those alternate lands.

Next Steps on Transparency

Transparency – which refers to publicly providing all necessary information to enable full, independent, third-party analysis of the effectiveness of NbCS initiatives (including location, nature, and all information that an external analyst would need to recalculate the benefits and understand the source of data and assumptions) – is paramount for ensuring rigorous and successful NbCS outcomes. Transparency in NbCS carbon credits is higher than in many NbCS interventions, but more is still urgently needed. Transparency is essential for independent and third-party assessment of project and program success in delivering on promised climate goals. Transparency is needed for the datasets, meta-data and models/tools used in program and protocol design, including baselines, leakage, and durability risks. Transparency at a project level is crucial in terms of the location and project physical boundary (e.g. shapefile), forest composition and age, the design and validation of remote sensing data sets, management history and proposed management changes, and other dimensions of project design. Transparency in the claims made and calculations of emissions reductions or removals is critical, especially as there is movement in this space to shift towards mitigating emissions within a corporation's value chain. Within value chain mitigation activities for companies must provide the same level of transparency expected elsewhere in the NbCS space so that uncertainties, assumptions, and limitations are not simply hidden behind proprietary walls.

Transparency practices vary widely in the voluntary carbon market today. Most carbon crediting programs provide some information about how climate benefits are calculated, but coverage varies and frequently excludes at least some relevant information. For example, it is uncommon for voluntary carbon market projects to provide shapefiles in their public registry listings. Industry norms and formal regulation are both encouraging additional disclosures through voluntary standards from the Integrity Council for the Voluntary Carbon Market and a mandatory disclosure law in California known as Assembly Bill 1305, the Voluntary Carbon Market Disclosure Act. Voluntary carbon registries should update protocols to require the key components of transparency for projects.

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Supplementary Boxes, Figures, and Tables

----------------------------------- Box S1: Definitions and Key Terms-----------------------------------

Additional: NbCS efforts that lead to climate mitigation beyond what would have happened absent those efforts, typically assessed as compared to a counterfactual baseline scenario. For example, if a given forest was unlikely to be degraded or deforested absent the NbCS initiative, but a carbon credit claimed that its baseline scenario involves significant degradation or deforestation, then the avoided emissions are likely not additional.

Avoided Conversion: Avoided conversion protocols in carbon markets that are supposed to prevent forests likely to be converted to remain standing.

Afforestation: Direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land.

Albedo: Reflectivity of a surface, primarily used here in terms of the visible/shortwave radiation spectrum.

Carbon credits: A quantified reduction or removal of greenhouse gas emissions that purportedly represents one ton CO_2e reduced or removed from the atmosphere for a predetermined period of time, which can be used to make either compensation (e.g. offsetting) or contribution claims.

Carbon offsets: Carbon credits that are used to justify a compensation claim.

Compensation claim: A claim that an entity's greenhouse gas emissions have been canceled out, negated, or neutralized. Most people who use the term "carbon offsets" are referring to the use of carbon credits to justify a compensation claim.

Compliance carbon market: A market for emission allowances and/or carbon offset credits that is established, run, and regulated by a government body to meet regulatory requirements.

Contribution claim: A claim that an entity has provided a financial contribution to a NbCS or other climate mitigation activity beyond its own value chain, without claiming to cancel out, negate, or neutralize any of their own emissions. Instead, they can claim they have contributed to global climate mitigation efforts, whether through the procurement of carbon credits or other mechanisms to support external climate mitigation efforts.

Improved Forest Management: Improved forest management changes in forest management designed to reduce emissions from forest management, reduce risk, and/or increase carbon stocks within a forest.

Jurisdiction: The extent of a government authority over a particular geographic area. In the NbCS space, jurisdictions are increasingly used for REDD+ programs. Typical jurisdictions are subnational (e.g. Acre, Brazil) or national (e.g. Guyana).

Leakage: The indirect impact and corresponding spatial shifting of an NbCS activity in one place and time on carbon storage in another place and/or time, which reduces the net effect of the intended intervention.

Methodology or Protocol: The rules that carbon crediting programs set for designing and implementing different kinds of carbon crediting projects. Each methodology includes eligibility criteria, methods for assessing emissions reduced or carbon removed, and methods for monitoring these reductions or removals for a specific project type or family of project types.

NbCS: Human actions that protect, better manage, and restore nature for climate mitigation.

REDD+: A climate mitigation framework that stands for reducing emissions from deforestation and forest degradation and other activities to enhance forest carbon stocks, developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC).

Reforestation: Establishment of forests on land that was previously forested, but currently is not (e.g. due to historical land clearing).

Registry: An entity that issues carbon credits such as Verra, the American Carbon Registry, the Climate Action Reserve, or Gold Standard.

Reversal: A reversal occurs when credited carbon that is stored outside the atmosphere is emitted or committed to be emitted to the atmosphere (e.g. when a tree dies from drought or fire). Carbon crediting programs often distinguish between avoidable reversals (such as elective decisions to harvest timber) from unavoidable reversals (such as a wildfire caused by lightning).

Voluntary carbon market: A market for trading carbon credits typically established and run by a non-governmental body, traditionally developed to help carbon credit buyers achieve voluntary emissions reduction goals.

-- END BOX --

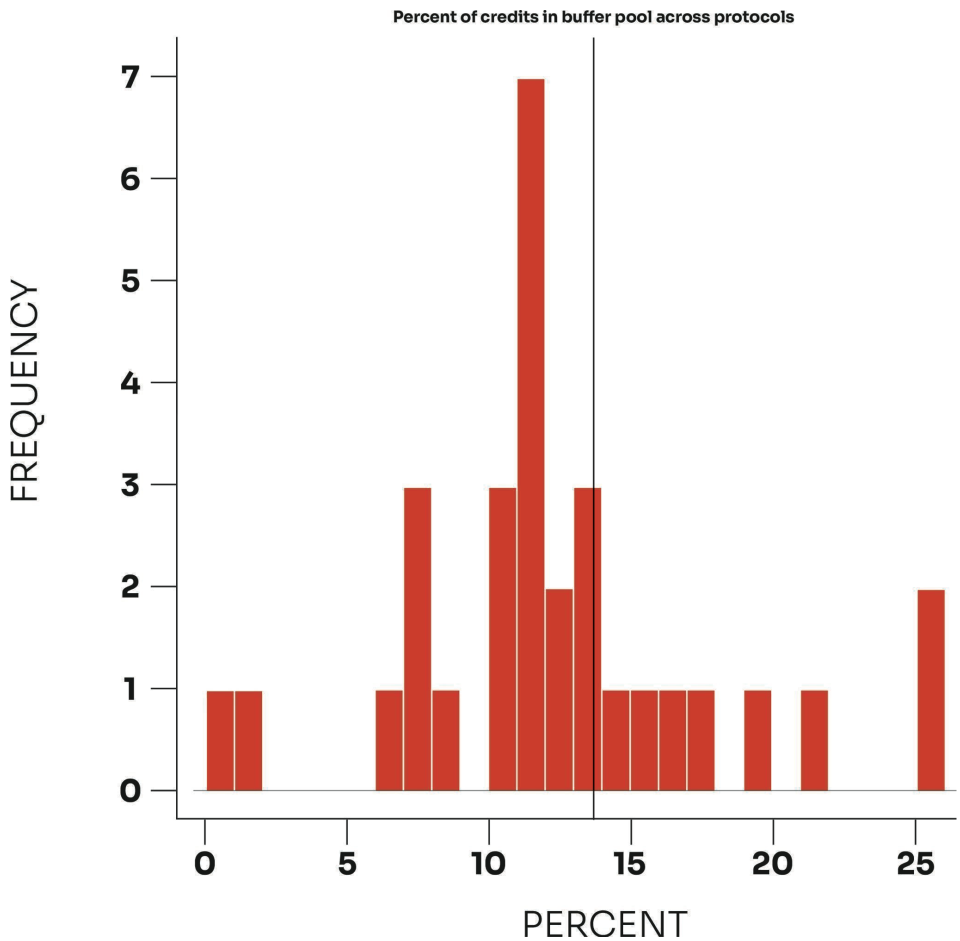

Figure S1: Buffer pool total sizes as a percentage of credits issued across currently active protocols in the voluntary carbon market as of December 2023. Black line is the credit-weighted average across protocols.

Supplementary Tables

Current Problem	Immediate Solutions	Near-Term Solutions and Research Needs
Net Climate Impact - No NbCS efforts to date account for the total climate impact of a given intervention - Changes in albedo may weaken or reverse climate benefits of reforestation or avoided deforestation efforts in some regions	Voluntary carbon registries and compliance market bodies should: - Incorporate albedo in NbCS carbon crediting protocols, and consider it in protocols for interventions and initiatives where albedo change is likely high (**Data**: Ref 38) - Disallow projects in places where albedo change outweighs the carbon storage benefit and fractionally reduce estimated climate benefits based on albedo changes	- Models and maps of the net climate impacts of a change in forests on cloud feedbacks, VOC and aerosol effects on climate, including direction and relative importance of different processes - Hydrologic cycle feedbacks (e.g. evapotranspiration) quantified and included in net climate impact maps
Durability - Most NbCS efforts do not base durability risks (e.g. buffer pool size) on robust, independent, spatially-varying data on natural and social risks - The role of climate change in increasing durability risks is rarely considered - Durability commitment is often far shorter (e.g. 20-40 years) than that needed for realizing climate mitigation benefits (>70-100 years) - Physical incommensurability of temporary forest carbon compared to fossil fuel carbon	Voluntary carbon registries and compliance market bodies should: - Update buffer pool contributions used by major forest NbCS efforts to reflect the current science (**Data**: Refs 61-62) - Use independent durability risk maps instead of projects selecting their own risk levels. - Strive for at least a 100 year lifetime in protocols - Allow durability mitigation to reduce buffer pool contributions only when based on empirical, region-, and intervention-specific science Carbon credit buyers should consider: - Durability of carbon storage needs to match the claim being made. Contribution claims could play a role	- Open-source tools to allow protocols and projects to extract their durability risk profiles for a given region, point, or project - Data-constrained and spatially-explicit estimates of the social risks to forest projects - Better inclusion of climate trends into durability risks and higher specificity for the risks by species or forest type - Syntheses on which management actions influence disturbance risk by biomes and regions - Liability could be transferred to the buyer of the carbon credit in the case of a reversal
Additionality - Extensive additionality and baseline problems in many NbCS protocols have led to widespread over-crediting - Little additionality has	Voluntary carbon registries and compliance market bodies should: - Shift to dynamic baselines where feasible - Improve jurisdictional baselines, which should be based on the best-available, consistent,	- Improvements in remote-sensing and ground measurements to map carbon stocks and fluxes at high resolution - Development of accurate and dynamic maps of past,

Current Problem	Immediate Solutions	Near-Term Solutions and Research Needs
been observed post hoc in most analyses to date	transparent, and independently-derived estimates of future forest loss and forest management Registries and carbon credit buyers should: - Increase transparency of baselines	current, and projected future management practices for additionality tools
Leakage - Leakage estimates in most NbCS protocols are too coarse and likely underestimated - Robust calculation of both activity and market leakage are exceptionally challenging to do currently	Voluntary carbon registries and compliance market bodies should: - Base leakage zones upon independently developed, third-party data and tools - More rigorously quantify leakage mitigation activities and not assume that activities eliminate all/most leakage - Require a market leakage deduction and account for international market leakage when a project reduced production of a commodity - Update leakage rates to conservatively reflect rates documented in the literature	- Maps and time-series datasets to distinguish the drivers (natural and human-driven) of forest loss over a region - Fusion of forest economic and land-use models with remote-sensing data to yield extensively-validated regional leakage rates - Shift to focus on projects where the climate benefits are unlikely to be undone by leakage
Structural challenges - Low transparency of direct emissions reductions vs carbon credits - Low transparency of climate benefit calculations - Lack of independence of verifiers creates potential conflicts of interest - Offsets and ton-for-ton accounting incentivize a 'race to the bottom' - Increasing legal risks to buyers of low-quality offsets	Policy-makers should: - Require separate disclosure of organization's direct emissions reductions and carbon credits used - Require transparency of critical data for recreating NbCS project climate benefits, including geographic boundaries, and baselines Voluntary carbon registries and compliance market bodies should: - Restructure verification process to financially decouple verifiers from project developers Carbon credit buyers should: - Expand funding models to include money-for-ton and money-for-money approaches	- Policy needed to require improved transparency - Further implement and test alternate claiming mechanisms, including a contribution approach to NbCS - Fund independent assessment of program effectiveness and dataset/tool development and updates

Table S1: Outline of steps towards more rigorous NbCS in forests with current problems, immediate solutions, and near-term solutions and research needs in each of the four components of rigor and structural challenges.

Registry	Minimum Lifetime	Project Type/ Activities	Methodology/Protocol	N Reg Proj	Issued Credits to 12-2023
ACR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	4	7891272
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	55	120182254
ACR Voluntary	40	ARR	AR-ACM0001: Afforestation and Reforestation of Degraded Land	2	6285796
		IFM	Improved Forest Management (IFM) on Non-Federal U.S. Forestlands	71	21290376
CAR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	1	244767
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	70	74329960
CAR-Mexico	30	Forestry - MX	Mexico Forestry Protocol	150	3882275
CAR Voluntary	100	AC	U.S. Forest Protocol	5	1434257
		Conservation	U.S. Forest Protocol	2	464044
		IFM	U.S. Forest Protocol	17	8914408
GS	30	A/R	Afforestation/Reforestation GHG Emissions Reduction & Sequestration Methodology	23	5276349
Verra	20	ARR	AR-ACM0001: Afforestation and reforestation of degraded land	9	18547279
			AR-ACM0002: Afforestation or reforestation of degraded land without displacement of pre-project activities	1	58122
			AR-ACM0003 Afforestation and reforestation of lands except wetlands	41	12125521
			AR-AM0003: Afforestation and reforestation of degraded land through tree planting, assisted natural regeneration and control of animal grazing	1	42625
			AR-AM0005: Afforestation and reforestation project activities implemented for industrial and/or commercial uses	1	753975
			AR-AM0014: Afforestation and reforestation of degraded mangrove habitats	5	1678419
			AR-AMS0001: Simplified baseline and monitoring methodologies for small-scale A/R CDM project activities implemented on grasslands or croplands with limited displacement of pre-project activities	10	1782813
			AR-AMS0005: Simplified baseline and monitoring methodology for small-scale afforestation and reforestation project activities under the clean development mechanism…	1	78003
			AR-AMS0007: Afforestation and reforestation project activities implemented on non-wetlands	2	177917
		IFM	VM0003 Methodology for Improved Forest Management through Extension of Rotation Age	2	347696
			VM0005 Methodology for Conversion of Low-Productive Forest to High-Productive Forest	2	522431
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	11	5638882
			VM0011 Methodology for Calculating GHG Benefits from Preventing Planned Degradation	1	182347
			VM0012 Improved Forest Management in Temperate and Boreal Forests (LtPF)	5	5876946
		REDD	VM0004 Methodology for Avoided Planned Land Use Conversion in Peat Swamp Forests	1	33625616
			VM0006 Methodology for Carbon Accounting for Mosaic and Landscape-scale REDD Projects	3	7592929
			VM0007 REDD+ Methodology Framework	26	135341480
			VM0009 Methodology for Avoided Ecosystem Conversion	8	68125930
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	2	241539
			VM0015 Methodology for Avoided Unplanned Deforestation	20	56477932

Table S2: Forest NbCS carbon credits issued as of December 2023 by registry, project type, protocol, and minimum required project lifetime.

Perspective

Towards more effective nature-based climate solutions in global forests

https://doi.org/10.1038/s41586-025-09116-6

Received: 12 July 2024

Accepted: 8 May 2025

Published online: 30 July 2025

Check for updates

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Terrestrial ecosystems could contribute to climate mitigation through nature-based climate solutions (NbCS), which aim to reduce ecosystem greenhouse gas emissions and/or increase ecosystem carbon storage. Forests have the largest potential for NbCS, aligned with broader sustainability benefits, but—unfortunately—a broad body of literature has revealed widespread problems in forest NbCS projects and protocols that undermine the climate mitigation of forest carbon credits and hamper efforts to reach global net zero. Therefore, there is a need to bring better science and policy to improve NbCS climate mitigation outcomes going forward. Here we synthesize challenges to crediting forest NbCS and offer guidance and key next steps to make improvements in the implementation of these strategies immediately and in the near-term. We structure our Perspective around four key components of rigorous forest NbCS, illuminating key science and policy considerations and providing solutions to improve rigour. Finally, we outline a 'contribution approach' to support rigorous forest NbCS that is an alternative funding mechanism that disallows compensation or offsetting claims.

Terrestrial ecosystems play an important role in contributing to climate mitigation, acting as a substantial carbon sink and absorbing an estimated 31% of anthropogenic carbon emissions per year (ref. 1). Ambitious efforts to rapidly reduce fossil fuel emissions remain the most important components of climate mitigation, but there is growing interest in interventions that reduce emissions from and/or increase carbon storage in terrestrial ecosystems through NbCS to supplement and accelerate climate mitigation[2–5]. Of all the proposed NbCS management actions, those implemented in forests have the largest potential for further climate mitigation[2,6]. Given that deforestation at present leads to 1.9 GtC year^{-1} of emissions[1], actions to halt and reverse deforestation are a critical part of climate stabilization pathways[7].

NbCS in forests are increasingly funded by a range of public and private sources[8], using various management actions, including avoided forest conversion/deforestation, reforestation (sometimes combined with afforestation; Supplementary Information Box 1), improved forest management and agroforestry. Substantial interest by the private sector to meet climate commitments has spurred further sources of funding, often channelled towards buying NbCS carbon credits from voluntary and compliance markets[9,10]. Forest NbCS can also provide climate adaptation benefits for local communities, as well as other important co-benefits for people and biodiversity[4,11], but to succeed specifically as 'climate solutions', NbCS must provide rigorous and effective climate mitigation, defined here as emissions reductions and/or carbon removals that decrease global net radiative forcing through global peak warming (Fig. 1).

At present, carbon credits are an important way for private contributors and governments to invest in NbCS and could potentially play a larger role in the future. Unfortunately, a broad body of literature has identified widespread problems with how forest NbCS initiatives through carbon credit markets have accounted for their climate impact[12–26]. Many programmes have issued credits that achieve only a small fraction of what they claim in terms of climate mitigation benefits, which undermines climate progress, particularly when claimed as offsets. Driven by widespread concerns around effectiveness, the present price of carbon credits from tropical forestry NbCS projects fell from a high of more than \$21 per ton CO_2e to around <\$1–2 per ton CO_2e in 2024 (ref. 27). Thus, there is an urgent need to bring better science and policy to bear in directing private and public funds to NbCS that deliver effective climate benefits at scale.

Although several recent publications have developed core principles for improving NbCS quality[5,6,11,15,28–32], we lack a clear vision for doing so at present. Improvements are needed for programme design and for funding mechanisms and the claims made by those buying credits. Here we describe how substantial improvements in NbCS effectiveness and rigour could be made immediately and over the near-term

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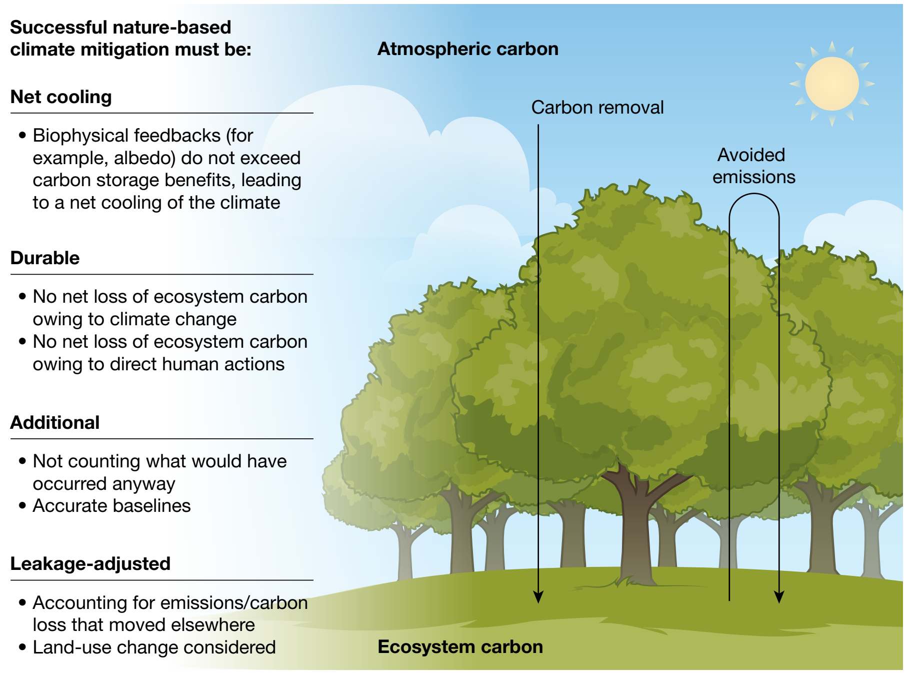

Fig. 1 | Key criteria for effective climate mitigation in forests. Central pathways of avoided emissions and carbon removal and four central criteria for rigorous and effective climate mitigation in NbCS in forests. We note that 'No net loss of ecosystem carbon' under the 'Durable' category means losses beyond what an insurance or compensation mechanism, such as a buffer pool, would cover.

(for example, the next 5 years) (Supplementary Table 1). We first review four critical components (net climate cooling, durability, additionality and leakage) required for NbCS effectiveness and rigour. For each component, we provide an overview of the concepts, problems with present approaches used by carbon crediting methodologies and how better science and data can help address these problems in the near-term (Supplementary Table 1). Finally, we conclude with structural reforms needed to drive rigorous NbCS and illustrate how an alternative to the traditional offsetting approach—a contribution approach—could sidestep many structural challenges in an offsetting framework. We refer readers to Supplementary Information Box 1 for clarification of key terms and concepts.

Four key components of improved NbCS

To succeed with climate mitigation, forest NbCS efforts must satisfy four key components (Fig. 1). Activities must lead to a net global climate cooling by integrating both changes in atmospheric greenhouse gases and biophysical feedbacks, store carbon for a sufficiently long period while accounting for the risk of losses, result in further climate mitigation benefits relative to what would have occurred without the intervention and avoid substantial negative impacts from leakage or the shifting of activities to other parcels of land[5,28]. There are other important social and ethical considerations to take into account, including responsible ecological design, doing no harm to biodiversity or people and respecting community land rights and indigenous communities, which have been covered extensively in other reviews[4,5,11,33]. We focus this Perspective on how to deliver these key scientific components for rigorous and effective forest NbCS climate mitigation.

Net climate cooling

Forests alter climate at local to global levels by modulating water, energy, carbon, volatile organic compounds and aerosols in the atmosphere[34]. These impacts can be loosely binned into 'biogeochemical' and 'biogeophysical' effects, although interactions between the two types of effects occur (Fig. 2). Biogeochemical effects describe how forests influence carbon and nutrient cycles, as well as volatile organic compound emissions, aerosol formation and atmospheric chemistry. Biogeophysical impacts capture how forests mediate water and energy exchanges between the land and atmosphere.

Albedo is an important biogeophysical effect and exerts first-order control on the net surface radiative balance of the Earth system. Forests tend to have lower albedo than other land surfaces[34–36] and absorb a larger fraction of incident solar radiation, warming the climate. Thus, persistent changes in forest cover—both losses and gains—will change albedo and will affect the climate mitigation benefit of both avoided forest conversion and reforestation initiatives[35–38]. Some landscapes are particularly reflective—such as places with persistent snowpack, bright soils or grasslands. In these landscapes, trees can substantially reduce albedo. The relative importance of albedo depends on carbon storage within the forests. In places in which carbon storage is high and albedo change is low, accounting for albedo will not substantially alter climate mitigation estimates of a project. But there are places in which the reduction of albedo can outweigh the carbon storage within the system, such as boreal forests or semi-arid drylands with sparse vegetation[38,39]. Quantifying this albedo change is thus essential for understanding where forest projects might provide a net climate benefit.

For improved forest management, the degree to which albedo is a concern remains uncertain but is probably small. The relationship between stand age and albedo tends to be nonlinear and saturating[37,40,41]. As a result, activities that maintain forest cover for longer periods of time (for example, extended rotations) may not result in substantial changes to albedo, but quantification of the albedo impacts of most improved forest management practices is scarce[37].

Solutions and research needs

Despite the potential for albedo to reduce or even negate the climate mitigation benefits of avoided conversion and reforestation, it is not considered in any carbon crediting protocols so far. Fortunately, albedo is readily measured by many remote-sensing platforms, and datasets that transform albedo changes into information relevant for carbon

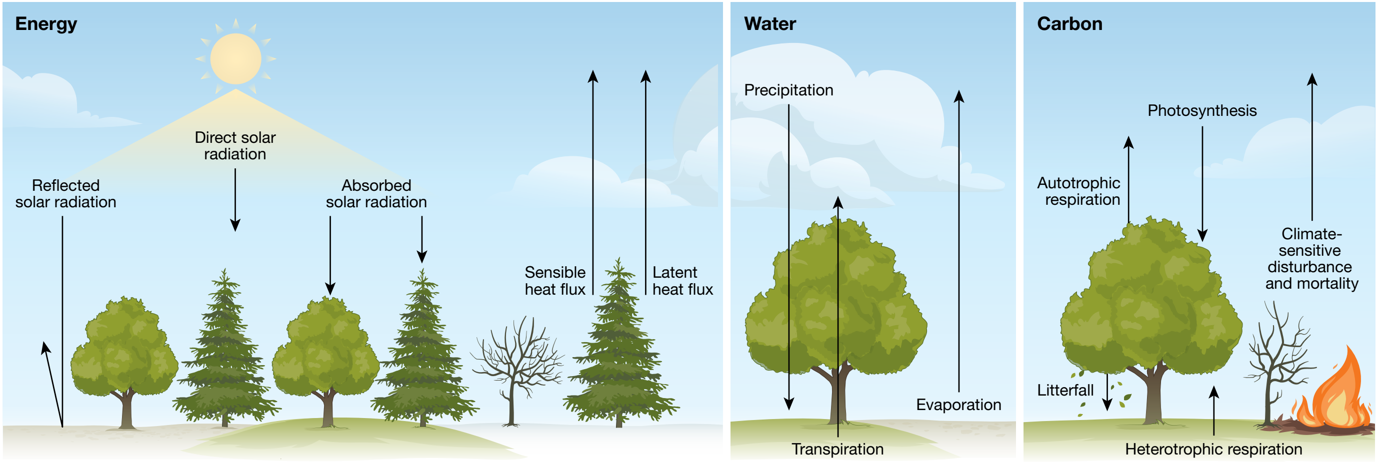

Fig. 2 | Key fluxes that mediate climate benefits of forests. Illustration of multiple key land–atmosphere interactions that mediate net climate impacts in energy, water and carbon cycles. Additional relevant feedbacks around clouds and circulation are not shown here.

accounting now exist[36,38,42]. Moving forward, albedo would ideally be incorporated in climate mitigation quantification of NbCS in two prominent ways (Supplementary Table 1). First, carbon projects should not be allowed in places in which warming induced by lowered albedo outweighs the carbon storage benefit[38]. A second method for accounting for albedo change would be to fractionally reduce the expected climate mitigation benefit (for example, credits) from individual projects based on the expected changes in albedo. More detailed sampling of albedos for a range of land cover, land management and land-use conditions in unique geographies is needed to improve rigour and accuracy. More robust consideration of effective radiative forcing (after dynamic Earth system adjustments) and its efficacy (the spatiotemporal patterning of its magnitude) relative to well-mixed, long-lived greenhouse gases is also important.

Key near-term future research needs include improved understanding, models and maps of the impacts of cloud feedbacks, volatile organic compounds and aerosol effects on climate[43]. Research is needed to distinguish the direction and relative importance of different feedbacks (surface albedo, volatile organic compounds and aerosols and clouds) at local and global scales (Supplementary Information). Finally, although a single project in isolation is unlikely to cause large changes in cloud cover and other hydrologic cycle feedbacks, implementing forest NbCS at large scales (such as jurisdictional REDD+ initiatives) is likely to cause substantial changes in cloud cover that may accentuate or reduce changes in surface albedo[44]. Therefore, such hydrologic cycle feedbacks should be quantified and considered in albedo accounting at regional scales.

Durability

The durability of carbon storage refers to the length of time over which carbon remains outside the atmosphere. Forests face increasing disturbance risks that can drive carbon losses and compromise durability[13,15,45], such as wildfire, drought, biotic agents (pests and pathogens), wind events, severe storms, sea-level rise and invasive species[45]. Forests frequently regrow after these disturbances—but not always[46,47]. Thus, the most critical disturbance risks for NbCS initiatives are those that are climate-sensitive, widespread, severe and increasing, leading to lower regional carbon stocks over decades[15]. Also, forests face a wide range of socio-economic risks that can lead to their conversion to other land uses and/or prevent reforestation.

The dynamics of CO_2 emissions to the atmosphere have important implications for the climate mitigation value of NbCS and, in particular, the durability outcomes needed to realize different climate mitigation benefits. On societally relevant timescales, owing to the long-lived nature of CO_2, burning fossil fuels causes an effectively permanent change to atmospheric CO_2 concentrations[48,49]. As a result, long-term global mean temperature outcomes are expected to be driven by cumulative CO_2 emissions, rather than the timing of those emissions[50–55]. To reduce peak global temperature, carbon must be stored outside the atmosphere for at least as long as it takes to reach global peak temperature (50–100+ years, depending on the emission scenario) and only as a complement rather than a substitute for rapid fossil fuel emissions reductions[56,57].

The durability of carbon storage needs to match the claim being made for a given NbCS intervention or carbon credit[55,58]. Many carbon crediting programmes today equate the climate mitigation value of forest NbCS with the effectively permanent damages from fossil CO_2 emissions[59]. Durability commitments—the period of time over which a project or programme commits to preserve and monitor credited carbon—in carbon credit protocols are not permanent and usually in the range 1–100 years (refs. 18,19,60). Most forest carbon credits issued so far have been under protocols with a minimum project lifetime of 20 years (Supplementary Table 2). Thus, in physical terms, nearly all real-world durability commitments are incommensurate with the climate impacts from CO_2 emissions.

The most common durability risk-management tool is called a buffer pool. To construct a buffer pool, the programme administrator establishes guidelines for assessing the risk of reversal (that is, carbon loss) from natural and social/economic factors across the durability commitment period and then projects set aside a percentage of the carbon credits based on the level of anticipated risk[16]. When there is a qualified reversal in the carbon crediting programme, the programme administrator retires carbon credits from the buffer pool equal to the calculated net carbon losses. The buffer pool of a programme functions like an insurance programme and is designed to compensate for unintended reversals of carbon credits over the durability commitments of enrolled projects.

Several studies have found that present buffer pools are probably inadequate[13,15,16,61]. Across all protocols and credits issued up to December 2023, the credit-weighted average buffer pool size was 13.7% of credits issued and the most common value was about 12% (Supplementary Fig. 1). By contrast, Haya et al. (2023) found that about 26% was probably a conservative floor for stand-clearing disturbance and timber harvest disturbances in REDD+ projects. Wu et al. (2023) observed that roughly 36% of area in California's compliance offset projects was projected to lose carbon over the twenty-first century in a mid-range emissions scenario.

Solutions and research needs

The buffer pool contributions used by considerable forest NbCS efforts are not at present based on current, rigorous science and need to be revised[15,16,19] (Supplementary Table 1). More rigorous disturbance and reversal data are now available and should be directly incorporated into policies and protocols immediately by updating buffer pool contributions[16,61–63] (Supplementary Information). Disturbance return intervals can be estimated from historical data and combined with simple demographic models to estimate carbon trajectories over 100-year periods[64], although this approach does not directly include future climate change impacts. Detailed integrated 100-year reversal risk estimates and buffer pool contributions are forthcoming for US forests and early estimates for global forests as well[62]. Instead of the present piecemeal approach, it would be more robust and consistent to use a spatially explicit durability risk map based on the latest science and developed by independent scientists.

Key data gaps for assessing durability risk include independent, open-source tools based on peer-reviewed studies that provide consistent and spatially explicit risk maps and buffer pool sizes for each disturbance type that include projected trends in occurrence and severity owing to climate change, higher specificity or granularity for the risks by species, forest and/or project type, revised data-constrained estimates of the social risks to forest projects and more research and syntheses on which management actions can meaningfully influence disturbance risk in specific biomes and regions. Considering the enormous uncertainty in natural and social durability risks, we recommend conservative buffer pool allocations that protect against more extreme scenarios. Finally, given the present uncertainty about how effectively and under what conditions management interventions can reduce natural reversal risks, we further suggest that any deductions to buffer pool contributions based on management interventions be minimal or zero unless risk-specific science is available. Projects could be rewarded post hoc if management actions reduced risks relative to previous expectations. This approach would be conservative with respect to the net climate mitigation benefits achieved by NbCS projects[65,66].

Additionality

Additionality addresses whether the NbCS activity leads to further climate benefit compared with what would have happened without the climate investment[67]. Because additionality depends on effectively estimating an alternative outcome (that is, a baseline counterfactual of what would have occurred without the NbCS investment), it can involve marked uncertainty[68] and, so far, has been the source of a substantial portion of overcrediting from NbCS carbon crediting protocols[19,20,22,23].

The challenges of appropriately determining baselines and additionality differ by project category. Additionality in reforestation/afforestation projects requires action—for example, tree planting or supported natural regeneration—beyond what would have occurred without the climate finance. Although additionality and baseline concerns are generally perceived to be lower with reforestation projects compared with avoided conversion or improved forest management, they still apply. Uncertainty remains around natural recovery, land-use change (for example, would previous land uses have continued or changed without the NbCS) and whether reforestation would have happened without the climate finance. For avoided conversion and improved forest management, which involve changes in practice over time rather than a particular action such as planting trees, additionality is largely defined as a change from the baseline. Avoided conversion baselines hinge on predictions of forest loss without the NbCS investment[22,69]. Additionality in improved forest management projects depends on projects changing land management practices as a result of NbCS investment (for example, NbCS funding led to extended timber harvest intervals or reduced impact logging)[19]. In practice, additionality and baseline requirements are handled in a variety of ways, but present tools have generally been inaccurate owing to uncertainty in true baselines and flexibility given to project developers' selection of baseline scenarios[17–19,70,71].

A broad body of recent peer-reviewed literature using post hoc evaluations has documented inaccurate and inflated additionality claims in projects across the world[17,20,23,24,26,70,72–74]. For example, several research papers on California's compliance improved forest management offset protocols have documented extensive overcrediting and little or no evidence of additionality across projects in the USA[17,20,23,24]. For a subset of 16 substantial tropical REDD+ avoided conversion projects, a recent large study estimated that only about 6% of estimated credits were probably additional and that inaccurate historic baselines of deforestation rates drove this notable overcrediting[22]. An extensive analysis of 182 reforestation projects in Australia's carbon offset scheme found little evidence of additionality, as project areas largely mirrored non-project areas[26].

Solutions and research needs

A range of recommendations have been made recently for improving additionality and baseline assessments for improved forest management[19], reforestation/afforestation[26] and avoided conversion/REDD+ (ref. 70) projects. Here we discuss two main trends in baseline setting for forest projects that could improve additionality if done well (Supplementary Table 1).

First, a move towards dynamic baselines should, in theory, improve additionality. Dynamic baselines involve matching project sites with control sites that are theoretically identical except for the project activity. The additionality within the project site is then evaluated relative to the control sites, rather than a historical counterfactual. Dynamic baseline methods are considered best practice for research assessing the performance of a forest programme or intervention[70] and are still fairly new in carbon crediting programmes, although their use is growing (Supplementary Information).

The value of dynamic baselines, however, will hinge on the appropriateness of the control sites, which hinges on the robustness of data sources within both the project and control sites. Dynamic baselines only make sense for project-level interventions in which appropriate control sites (for example, synthetic controls) are available. Advances in remote-sensing data and modern ground-based measurements to map carbon stocks and fluxes continuously over time (that is, annually) at relevant spatial scales will improve identification of appropriate control sites and dynamic baseline estimates[28,75,76]. Ultimately, full transparency of selection processes, algorithms, remote-sensing data quality and control plots will enable independent evaluation of the appropriateness of the comparison. Improved maps of past and present management practices, including timber harvest return intervals, location and type of agroforestry practices, will help improve rigour. Moreover, maps of management practices in the grasslands and agricultural lands are needed, as these are the baselines in most reforestation and avoided deforestation projects.

Second, there is growing interest in supporting avoided deforestation efforts at the jurisdictional level—across an entire country, state or province—rather than at individual parcels. Proponents argue that jurisdictional programmes can better account for leakage and reduce the potential for adverse selection[77,78]. Although well-designed jurisdictional programmes can be more effective than a mosaic of individual projects, jurisdictional baselines remain subject to marked uncertainty[79] that cannot be mitigated with dynamic baselines owing to the lack of appropriate controls. Many jurisdictional programmes, including ART TREES, set baselines using historical deforestation rates. Because these rates can change greatly from year to year in response to changes in global commodity prices and policies in other countries[80,81], the choice of benchmark historical rates is uncertain and any fixed approach could lead to adverse selection[82–84]. Also, accurate evaluation of programme effectiveness needs assessments of how well programmes address the drivers of deforestation in the particular jurisdiction. Historical baselines can also be inaccurate as applied to countries with stochastic trends in deforestation rates, including those with low historical deforestation rates that may face higher deforestation in the future[85]. And although jurisdictional programmes better address domestic leakage, none of the methodologies used today accounts for international leakage effects, such as market-mediated effects on commodity prices[18,86,87].

Leakage

Leakage occurs when an NbCS activity causes a shift in activity between the project area and another area outside the project area, which reduces or increases the net effect of the intended intervention. Two general types of leakage are considered in the literature: activity leakage (sometimes termed 'activity shifting leakage') and market leakage. Activity leakage occurs when a specific activity being reduced by an NbCS project (for example, deforestation) moves to another area. Market leakage occurs when an NbCS activity changes market conditions, for example, by reducing supply of timber in one region, which creates incentives for increasing timber supply elsewhere. Activity leakage can potentially be monitored directly, whereas market leakage cannot be monitored at the project level and instead must be estimated with economic modelling[88]. With market leakage, information is often transmitted through price. In interconnected markets, the results of outputs by various producers of different products are complex.

Activity leakage can theoretically be tracked by monitoring changes in deforestation or timber harvest rates with satellite imagery in a pre-established leakage zone around the project area[18]. Present NbCS methodologies estimate market leakage at the beginning of the project and typically apply the rate throughout the course of the project. Some, but not all, REDD+ methodologies estimate market leakage. In REDD+ methodologies that do estimate market leakage, only domestic market leakage is assessed and deducted, and international leakage is ignored, despite international leakage being known to occur with forest commodities[18].

Methodologies apply a leakage deduction to adjust the amount of credits issued to a project. Leakage deductions applied by Verra REDD+ projects are typically slightly low: 2.6% for activity leakage and 4.4% for market leakage[18]. The scientific literature suggests that market leakage varies between 10% and 70% for REDD+ projects and a meta-analysis found an average of approximately 40% carbon leakage across studies in the forest sector[18]. This suggests that projects generating credits under present market-based NbCS protocols are probably substantially underestimating leakage effects[18,88,89].

Solutions and research needs

Project developers should have less flexibility to define leakage zones and estimate baseline deforestation rates within it (Supplementary Table 1). Protocols should require a market leakage deduction when a project involves reduced production of a commodity. International market leakage should be accounted for and leakage rates should conservatively reflect rates documented in the literature based on independent datasets and tools. Market leakage should be deducted around the same time as the production is assumed to be reduced to avoid substantial overcrediting[19].

Distinguishing the drivers of natural and anthropogenic forest loss over a region, particularly at project-relevant scales, is a crucial research need[90,91]. Such datasets could be used to track whether anthropogenic drivers of forest loss increase in rate in areas beyond project boundaries as a result of the project. These rates should be characterized at relatively high spatial resolution (that is, 30 m) over time (for example, decades) before the establishment of a project to identify leakage as a period of increased forest loss relative to the typical background rates of loss. A combination of forest economic models and remotely sensed patterns of land management, timber harvest and deforestation could potentially be used to provide better data constraints on leakage. Models will probably need to capture the drivers of land-use change or forest management in a given region, be extensively validated on independent datasets to ensure confidence on projections over future decades and provide a detailed characterization of uncertainty.

Finally, given enormous uncertainty in leakage estimates at present and challenges in robustly estimating leakage rates in the near-term, protocols should focus on projects (types, regions and characteristics) for which there is greater confidence that the benefits are unlikely to be undone by leakage (Supplementary Information). Such projects increase carbon storage or reduce carbon storage loss with little decrease in production or usable land or are paired with activities that reduce leakage pressure (for example, pairing avoided conversion projects around urban areas with policies that increase urban density).

NbCS programme structural reforms

As well as the crucial scientific reforms needed for rigorous forest NbCS described above, structural reforms that affect both the supply and demand sides of NbCS initiatives are urgently needed. Voluntary reporting standards have required separate reporting of an organization's direct emissions and purchased carbon credits, but public disclosure is still limited, although requirements are coming in some jurisdictions[10,92,93]. To enable independent analysis of the effectiveness of corporate climate action and increase confidence, the location and nature of NbCS interventions used as offsets—as well as all information that an external analyst would need to independently recalculate the benefits and understand the source of data and assumptions—should be publicly available (Supplementary Information), as is now required for carbon credits under California's new law, AB-1305 (ref. 93).

Better transparency in methodology and measurements of NbCS projects and activities will also be crucial to developing rigour in NbCS initiatives. Although required transparent data will probably vary depending on the activity and protocol, we suggest that a minimum floor of required data for NbCS projects and initiatives include the digital geospatial data that accurately define geographic boundaries of the interventions, either the proposed intervention activities and how those depart from the previous 20+ years of land management for projects using a historical baseline or selected control plots/regions for projects using a dynamic baseline, carbon crediting modelling/graphs that clearly show the assumed baseline for each individual project, and how that baseline was calculated, and forest composition of the intervention area at the initiation of the project necessary for independent reproduction of crediting and baseline scenarios. Funding for the creation and maintenance of these transparent, open and easily usable datasets is important and could be game-changing if provided by public and/or philanthropic sources.

Structural independence of NbCS project verifiers is a crucial design change needed to remove potential or perceived conflicts of interest. Instead of the present structure of credit-producing programmes in which verifiers are hired by project developers, verifiers should be hired by programme administrators or separate independent parties[94]. Alternatively, verifiers could be required to be chosen randomly from a common pool, hired from pooled resources and rewarded for accuracy[95].

The contribution approach to NbCS

There are several reasons why considering an alternative approach to NbCS may be valuable. Existing NbCS carbon credits have marked challenges with quality, as discussed above, making it legally and reputationally risky for corporations and other buyers to make emission reduction claims using many of those credits[96]. Corporations increasingly face legal complaints and greenwashing accusations for making offsetting-related claims that are considered misleading or unsubstantiated, which can violate consumer laws[97,98].

Conventional offsetting is based on a ton-for-ton model, in which a person or company buys an equal number of carbon credits as the emissions they seek to 'offset'. This approach can drive demand for high-volume, low-cost carbon credits[99], which can have benefits by encouraging economies of scale, innovation and renewed investment, but also at present probably have less real climate mitigation impact[100]. The present offsetting approach has structural incentives built into it such that many actors involved in producing carbon credits benefit from inflated estimates of project climate benefit[18,32,101]. Thus, it remains an open question whether the existing system can be meaningfully reformed to deliver rigour and effectiveness in the next 5–10 years.

Opportunities in a contribution approach

The contribution approach is an alternative framework for corporations and other organizations to support NbCS without claiming the resulting emissions reductions or removals offset or neutralize their own greenhouse gas emissions[102]. Under a contribution approach, instead of using carbon credits to report lower net emissions, a buyer would claim that they have only made a financial contribution to global climate mitigation. The largest incentives for companies and other organizations to buy into a contribution approach are that contribution claims are more scientifically accurate, straightforward and legally defensible, reducing legal and reputational risks. Also, the alternative funding models in a contribution approach can help channel the financial resources of an organization to potentially more strategic and high-impact efforts to reduce emissions inside and outside traditional carbon markets.

A contribution claim can be more scientifically accurate and legally defensible than a conventional offsetting claim because it does not presume equivalence between the climate mitigation benefits of NbCS with the harms of greenhouse gas emissions. Given the difficulty of precisely quantifying NbCS interventions and the incommensurability of the CO_2 temporarily sequestered within NbCS to fossil fuel emissions[55,103], this approach allows stakeholders to recognize the climate and co-benefits of NbCS without claiming equivalence of emissions reductions.

Although contribution claims cannot support statements that companies have achieved carbon neutrality or net zero, companies might nevertheless consider a shift from offsetting to contribution claims to reduce legal and reputational risks. Consumer protection and false advertising laws prohibit false or misleading statements, which could present legal risks if a company relies on low-quality carbon credits to substantiate a carbon-neutrality or net-zero marketing claim. By contrast, contribution claims may be more responsive to, and present fewer compliance risks under, existing and emerging regulatory measures. For example, the European Parliament's recent revision to its Unfair Commercial Practices Directive[104] prohibits conventional offsetting claims for consumer products and suggests that contribution-type claims may be appropriate.

The contribution approach is compatible with many beyond value chain mitigation (BVCM) guidelines[105–107]. BVCM guidelines help corporations more credibly set science-based targets and engage with BVCM activities in a more transparent manner. These guidelines typically include recommendations that companies assign priority to direct emissions reductions, raise funds through ton-per-ton, money-per ton or money-per-money models, assign priority to the spending of such funds on effective climate mitigation and transparently making contribution and other more accurate claims.

When companies follow such BVCM guidelines, the contribution approach offers several potential advantages for advancing rigorous NbCS. The first advantage is that it facilitates fundraising strategies that could drive demand for higher quality NbCS, specifically by disconnecting demand for NbCS from a ton-for-ton compensation model. Alternatively, companies could use a money-per-ton approach in which they set an internal carbon fee (or tax) on their own emissions to encourage reductions and use fee revenues to fund NbCS or other BVCM approaches. BVCM guidelines recommend an internal carbon fee be set at the social cost of carbon, generally considered to be \$100 to >\$283 per ton[108–111] and higher in wealthy regions if equity weighting is used[112]. Alternatively, under a money-per-money fundraising approach, a corporation would commit a percentage of its annual profits or revenues to support rigorous NbCS. Both of these alternative fundraising approaches could change the incentive structure of demand for carbon credits to allow corporations to focus their set budget on high-quality climate mitigation initiatives. This could potentially create a 'race to the top' for high-quality NbCS initiatives both inside and outside carbon markets, rather than the present incentive for quantity. It also provides flexibility to channel financial resources to a wider pool of critical investments, for example, towards efforts that broadly decarbonize economic sectors and/or protect natural resources through system change, including advocacy for stronger climate and forest protection policies.

A second advantage of the contribution approach is that, if buyers shifted their focus to high-quality NbCS initiatives, project developers may have less incentive to inflate an initiative's climate benefit and more incentive to rigorously quantify it. Thus, project developers could be more open to the structural shift in third-party certification described above[32]. Such an incentive structure could also promote the development of, and demand for, NbCS quantification methods by independent analysts without conflicts of interest.

A third advantage is that the contribution approach allows entities to fund NbCS while quality issues and uncertainty around NbCS carbon credits remain. This is especially useful if revisions to incorporate the rigour outlined in this synthesis are delayed or not fully implemented in NbCS carbon crediting protocols. One example of contribution approaches already driving companies to financially support potentially high-quality initiatives as an advanced market commitment is the 'Frontier' initiative focused on accelerating the development of durable carbon-removal technologies.

Critics may argue that corporations might stop investing in NbCS if they can no longer make offsetting claims. However, research shows that corporations engage in carbon markets for reasons beyond reaching emission reduction targets[96,113]. Corporations also engage in carbon markets for market competitiveness (for example, as a branding tool) and to uphold and embody corporate values (for example, supporting the Sustainable Development Goals and to do their part for climate mitigation). In a recent study, about 31% of companies listed market competitiveness and about 32% listed corporate values as reasons for purchasing carbon credits[113]. These findings illustrate that, although some corporations may want to maintain an offset-claiming approach, many corporations already buy carbon credits for reasons that can be aligned with a contribution approach. Furthermore, it is not clear that consumers are swayed towards offsetting claims more than other types of claim. Rather, research indicates that public comprehension of green claim terminology—including climate claims—is low, even among the most environmentally engaged consumers[114,115]. This suggests that corporations can differentiate themselves from their competitors, potentially with more flexibility to tailor to their interests and values, and that consumers may not be strongly swayed one way or another between the advertising of a corporation making an offsetting versus contribution claim.

Another common concern is that the contribution approach could allow corporations to focus on charismatic (for example, compelling narratives around social or biodiversity benefits) projects with limited climate benefit. This is indeed an open question. In this scenario, the cost of funding the charismatic project itself is that the corporation's money has been spent less effectively on climate mitigation than it could otherwise have been. This is arguably better for the climate than when companies use ineffective carbon credits in lieu of real emissions reductions, which results in an increase in greenhouse gases in the atmosphere and climate damages[26]. Such risk can also be mitigated as third-party watchdogs, including civil society organizations, academic researchers and institutions, journalists and private sector ratings agencies, continue to examine the impacts of corporate climate funding[116].

Relatedly, a risk of the contribution approach is the decoupling of a corporation's residual emissions from support for climate mitigation elsewhere when the money-per-money fundraising pathway is chosen. This could potentially decrease the amount of funding channelled towards NbCS initiatives, at least initially. However, if rigorously identified and quantified NbCS initiatives were strategically funded, the real climate-mitigation impact-per-dollar would probably go up. Best practices recommend that the money-per-ton fundraising pathway should be used by high-profit companies, whereas the money-per-money pathway could be useful for the small percentage of heavy-emitting companies (for example, utilities, air travel, cement) that generate profits of less than \$100 per tCO_2 of emissions[117]. An estimated US\$27 billion per year could be generated if just 141 high-profit companies spent \$100 per ton they emit, representing a small percentage of their profits[117].

Contribution approaches are gathering interest around the world. Contribution claims are considered within the UNFCCC's Paris Agreement in both Article 6.4 as 'mitigation contribution units' and in Article 6.8 as 'non-market contributions'. In the voluntary context, the contribution approach is already being promoted and implemented by companies (for example, Klarna, Ocean Outdoor and United Airlines), climate finance project curators (for example, Milkywire and Pinwheel) and registries (for example, the Gold Standard). For the approach to be implemented more broadly, more demand for the approach could be generated if corporate climate standards required contribution claims. Also, third-party accreditation would help mainstream the approach. Nevertheless, the contribution approach is an increasingly promoted option for corporations and others interested in investing in BVCM in a more credible way and could contribute impactful, needed funding to rigorous NbCS.

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Acknowledgements This article is the product of the Wilkes Center for Climate Science and Policy at the University of Utah's Working Group on Rigorous Nature-based Climate

Solutions in Forests. We thank S. Cook-Patton, who was a co-author on the initial manuscript and contributed to idea generation, writing and revisions, but is not listed in the final draft owing to differences in opinions about final recommendations. We thank K. Riley and P. Ellis for providing feedback on this work. W.R.L.A. acknowledges support from US National Science Foundation grants 2003017, 2044937 and 2330582 and Alan T. Waterman Award IOS-2325700.

Author contributions W.R.L.A. and L.B. wrote the first draft of the manuscript. W.R.L.A., L.B., C.A., G.B., D.C., P.G., M.L.G., B.H., J.A.H., M.D.H., M. Lague, M. Liu, K.A.N., J.R., A.T.T., J.A.W., C.A.W., C.W. and L.Y. contributed to idea generation, literature synthesis, writing of several drafts and revisions.

Competing interests D.C. previously consulted for Isometric and is a member of the Milkywire Climate Transformation Fund Advisory Board, the UNFCCC Article 6.4 Mechanism Methodological Expert Panel and California's Independent Emissions Market Advisory Committee. The other authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-025-09116-6.

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Peer review information *Nature* thanks Jiehong Lou and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Towards more effective nature-based climate solutions in global forests

Supporting Information

Next Steps on Net Climate Impacts

We foresee two prominent ways that albedo could be incorporated into NbCS policies and protocols. These changes would be most important to incorporate into reforestation/afforestation protocols where a recent global analysis was published that enables direct quantification of albedo's impact[1]. First, voluntary carbon registries and compliance market bodies should revise protocols to use the 'albedo offset' map in Hasler et al. (2024)[1] to disallow afforestation or reforestation project development in grid cells where the radiative forcing impact from the change in albedo exceeds the radiative forcing benefit from carbon storage in a forest project. The 'albedo offset' map provides the fractional climate impact (radiative forcing) that albedo change would 'cancel out' from the carbon storage benefit of a given project. For example, a 50% albedo offset indicates that albedo change roughly negates around 50% of the climate mitigation benefit from carbon storage in a given grid cell. This exclusion threshold provides a very clear and straight-forward map of where the net climate impact of reforestation/afforestation is likely to be warming and thus should be avoided for programs with climate mitigation goals. We note that it might be useful to exclude projects that exceed a certain threshold of albedo offset lower than the 100% threshold (net warming) – a tiered approach – with the goal of conservative crediting, but this is a normative decision[2].

Second, voluntary carbon registries and compliance market bodies should revise protocols to fractionally reduce the credits issued using the 'albedo offset' map in Hasler et al.

(2024), in a similar manner to the current leakage deduction. Protocols could require carbon projects to upload a geographic project boundary or centroid point to the open-source tool from Hasler et al. (2024), extract the albedo offset for that project, and then adjust the crediting calculation by deducting the albedo offset fraction. Furthermore, projects could monitor albedo change with in situ or remote sensing measurements within the project boundary and update the albedo deduction dynamically with more granular, local data that would better account for specific project species composition, density, soil albedo, etc.

Concerning key near-term future research needs to improve the incorporation of cloud feedbacks, volatile organic compounds, and aerosol net climate impacts of NbCS projects[3–5], we believe a coordinated set of modeling experiments is needed to advance these areas to provide implementation-ready tools. In particular, a comprehensive series of model experiments that would generate Green's Function across a range of climate models (similar to those produced for sea surface temperatures[6,7]) to characterize climate response to local-to-regional scale changes in albedo evapotranspiration, VOCs, and aerosol emissions, individually, would be a critical step to moving beyond the radiative kernel approach from albedo[1]. This would capture not only the instantaneous local radiative effect of a change in land albedo, but also the change in planetary albedo (impacted by clouds and other processes) that is critically necessary for global (not just local) temperatures. Such Green's Functions could also be produced for other key surface properties (e.g. relating to aerodynamics and evaporation). The key difference between a radiative kernel versus a Green's Function is that the radiative kernel provides the instantaneous radiative effect of a given change (e.g. in land surface albedo at one location), without any adjustments or feedbacks to that change, while a Green's Function quantifies the full system response to a given change (e.g. a change in land surface albedo at one location), which is composed of the direct instantaneous effect and all the responses and feedbacks within the system[8].

Kernels are generated by running the radiative transfer code of a model offline at each timestep, once with no change (these are the fluxes passed to the model to integrate forwards) and once with the imposed change (e.g. in surface albedo; these fluxes are saved to the kernel, but are not passed to the model for the next time step – the model is unaware any change was made to surface albedo). In contrast, a Green's Function has a change imposed on it that impacts the forward integration of the model – the change in albedo alters surface and top-of-atmosphere (TOA) fluxes which alter atmospheric processes which potentially feedback on surface and TOA fluxes[8].

In the Green's Function experiment, a substantial amount of the net surface and net TOA radiative fluxes are mediated by atmospheric feedbacks to the surface change. In the radiative kernel, there are, by design, no feedbacks. The Green's Function approach has an additional benefit of not being restricted to local effects - it could capture changes in circulation. The radiative kernel can only capture the direct effect on the local column radiation balance.

Because a radiative kernel doesn't need to propagate information from imposed perturbations in either space or time, one can generate a kernel with one coupled model run. In contrast, a Green’s Function approach requires running a fully coupled land-atmosphere simulation for each location one is interested in perturbing. This likely makes it impractical to run for a given NbCS project, but could theoretically be run for a substantial forest cover change within a jurisdiction. Thus, a suite of model experiments that developed Green’s Functions for a range of NbCS jurisdictions across a range of climate models could provide a quantitative key basis of these additional feedbacks on radiative forcing and maps that could be incorporated into protocols similar to the approach described with albedo above, although uncertainties in constraining net TOA fluxes from satellites may be a barrier[9].

Next Steps on Durability

The immediate next steps to update buffer pools with the best-available science involve voluntary carbon registries and compliance market bodies updating protocols to require that buffer pool sizes and contributions be calculated from an independent, third-party dataset that provides rigorous buffer pool calculations that include climate change trends[10,11]. Similar to albedo, project developers would use an easily-accessible web tool to upload a geographic boundary file or centroid coordinate of the project and receive a buffer pool contribution set of scores. This initial tool provides disturbance-specific buffer pool sizes for wildfire, drought, and insect outbreaks in the United States and a single combined 'stand-replacing' disturbance score for forests globally. This tool can and should be updated to include additional granularity of other disturbances, such as wind and storm disturbances, and disturbance severity at jurisdiction and global scales. We note that there is substantial complexity, which is beyond the scope of this review paper to cover, around how buffer pools are capitalized and tapped by reversals that vary by protocol that must be carefully addressed in protocol updates[12].

Next Steps on Additionality and Baselines

The two approaches we highlight as potentially promising for baseline assessment that avoids overcrediting—dynamic baselines and jurisdictional approaches—are just starting to be used to generate carbon credits and so ongoing research on their effectiveness is needed to refine them over time, and to assess if they are able to reasonably avoid significant overcrediting. This analysis should be performed by independent researchers (i.e. without interest in the outcomes) either on their own or under contract by program administrators. Transparency is necessary to enable external analysis, and involves providing all the information needed for external analysts to assess data sources and assumptions, and to reproduce the baseline calculations, as required in California bill AB 1305 and as is standard for academic articles. Further, program administrators should nimbly improve methodologies as understanding improves. A shift to a contributions approach facilitates this process of analysis and improvement by reducing the legal risk associated with discovering that previous scientific understanding resulted in excess crediting.

Core datasets for estimation of dynamic and jurisdictional baselines include time-series calculations of carbon stocks (e.g. aboveground live carbon) from forest inventory plots and/or from rigorously-validated remote-sensing products, time-series maps of land use (e.g. agriculture, forest), and time-series maps of land management (e.g. timber harvest, forest degradation). Other ancillary data around climate, forest type, soil, distance to road, and land ownership data will also likely be important for dynamic baselines[13,14]. These remote-sensing products will likely need to be at high enough resolution to detect project-level changes and establish robust comparison control pixels to project pixels.

Dynamic baselines are considered best practice for baselines in the context of many similar activities and actors. Adverse selection remains a risk with dynamic baselines since methods for establishing control plots cannot capture all factors that affect what would have happened without the carbon finance[15].Other baseline-setting methods are needed for certain locations or landowner types where dynamic baselines are not viable[16]. For these, more research is needed to determine effective baseline setting methods.

Dynamic baselines can also account for additionality when baselines are an effective measure of additionality. Additionality and baselines are different assessments when projects involve a discrete action, like restoring a degraded forest, rather than a change in forest management over time such as extended rotations. For these projects, dynamic baselines can assess the baseline, but a separate additionality assessment is also needed. Additionality assessments involve understanding of the specific location and factors affecting decisions in that context which should be performed by independent analysts with contextual knowledge on a project category or individual project basis.

On jurisdictional REDD+, in addition to the datasets described above, multi-method case study analyses of specific programs will be important to explore how effectively programs address deforestation drivers and how criteria can be improved for determining which jurisdictional programs meet basic quality criteria. Effectiveness criteria includes how well programs address deforestation drivers, fairly engage with forest-dwelling communities in program design and implementation, and set accurate and conservative baselines.

Until we have more experience with these new baseline methods and they have been demonstrated to be reasonably accurate, baseline setting should lean heavily towards conservativeness to avoid the previously-observed pervasive overcrediting.

Next Steps on Leakage

Concerning flexibility in leakage zones, leakage zone calculations could be required to use an independent, third-party tool similar to the approach proposed here for buffer pool contributions for durability. Furthermore, prescribed minimum floors of activity leakage could at least partially address the challenges around flexibility.

Leakage mitigation can take many forms. For REDD+, leakage mitigation activities can involve addressing underlying drivers of deforestation, including by engaging local communities in program design, and coordinating across broader geographical scales to manage land use changes comprehensively[17,18]. In general, when an NbCS project results in a reduction in production (e.g., timber or agriculture), mitigation activities can increase production in ways that do not lead to further loss of forest carbon, such as pairing extended rotation projects with forest restoration activities that include thinning, and forest protection with agricultural intensification. The outcomes of these mitigation activities should be monitored and conservatively quantified and leakage deductions should be made for the portion of leakage not made up by mitigation activities. More rigorous quantification of the effectiveness of some of these activities could involve periodic re-assessment of activity leakage rates with remote sensing data[19].

Models can help illuminate how the expected magnitude of leakage varies by region, project type, market, and policy coverage. Higher leakage rates are expected where policy coverage is narrow (e.g. smaller geographic scales), smaller scales of activity displacement, more connected or integrated markets, higher producer flexibility in the market, availability of proximal alternative lands for production, and higher carbon emissions from the leakage zones than the project areas[18,20]. Policy coverage and scales of activity displacement are generally known at a protocol-level via what regions are in scope and how many projects have been developed or proposed to date. Market connectivity and producer flexibility are more challenging to estimate but a range of social science and econometric methods can provide insights and constraints. The availability of relevant nearby alternative lands and carbon emissions from the leakage zones can partially be estimated with remote-sensing data to track similar lands to proposed projects and carbon losses from those alternate lands.

Next Steps on Transparency

Transparency – which refers to publicly providing all necessary information to enable full, independent, third-party analysis of the effectiveness of NbCS initiatives (including location, nature, and all information that an external analyst would need to recalculate the benefits and understand the source of data and assumptions) – is paramount for ensuring rigorous and successful NbCS outcomes. Transparency in NbCS carbon credits is higher than in many NbCS interventions, but more is still urgently needed. Transparency is essential for independent and third-party assessment of project and program success in delivering on promised climate goals. Transparency is needed for the datasets, meta-data and models/tools used in program and protocol design, including baselines, leakage, and durability risks. Transparency at a project level is crucial in terms of the location and project physical boundary (e.g. shapefile), forest composition and age, the design and validation of remote sensing data sets, management history and proposed management changes, and other dimensions of project design. Transparency in the claims made and calculations of emissions reductions or removals is critical, especially as there is movement in this space to shift towards mitigating emissions within a corporation's value chain. Within value chain mitigation activities for companies must provide the same level of transparency expected elsewhere in the NbCS space so that uncertainties, assumptions, and limitations are not simply hidden behind proprietary walls.

Transparency practices vary widely in the voluntary carbon market today. Most carbon crediting programs provide some information about how climate benefits are calculated, but coverage varies and frequently excludes at least some relevant information. For example, it is uncommon for voluntary carbon market projects to provide shapefiles in their public registry listings. Industry norms and formal regulation are both encouraging additional disclosures through voluntary standards from the Integrity Council for the Voluntary Carbon Market and a mandatory disclosure law in California known as Assembly Bill 1305, the Voluntary Carbon Market Disclosure Act. Voluntary carbon registries should update protocols to require the key components of transparency for projects.

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Supplementary Boxes, Figures, and Tables

----------------------------------- Box S1: Definitions and Key Terms-----------------------------------

Additional: NbCS efforts that lead to climate mitigation beyond what would have happened absent those efforts, typically assessed as compared to a counterfactual baseline scenario. For example, if a given forest was unlikely to be degraded or deforested absent the NbCS initiative, but a carbon credit claimed that its baseline scenario involves significant degradation or deforestation, then the avoided emissions are likely not additional.

Avoided Conversion: Avoided conversion protocols in carbon markets that are supposed to prevent forests likely to be converted to remain standing.

Afforestation: Direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land.

Albedo: Reflectivity of a surface, primarily used here in terms of the visible/shortwave radiation spectrum.

Carbon credits: A quantified reduction or removal of greenhouse gas emissions that purportedly represents one ton CO_2e reduced or removed from the atmosphere for a predetermined period of time, which can be used to make either compensation (e.g. offsetting) or contribution claims.

Carbon offsets: Carbon credits that are used to justify a compensation claim.

Compensation claim: A claim that an entity's greenhouse gas emissions have been canceled out, negated, or neutralized. Most people who use the term "carbon offsets" are referring to the use of carbon credits to justify a compensation claim.

Compliance carbon market: A market for emission allowances and/or carbon offset credits that is established, run, and regulated by a government body to meet regulatory requirements.

Contribution claim: A claim that an entity has provided a financial contribution to a NbCS or other climate mitigation activity beyond its own value chain, without claiming to cancel out, negate, or neutralize any of their own emissions. Instead, they can claim they have contributed to global climate mitigation efforts, whether through the procurement of carbon credits or other mechanisms to support external climate mitigation efforts.

Improved Forest Management: Improved forest management changes in forest management designed to reduce emissions from forest management, reduce risk, and/or increase carbon stocks within a forest.

Jurisdiction: The extent of a government authority over a particular geographic area. In the NbCS space, jurisdictions are increasingly used for REDD+ programs. Typical jurisdictions are subnational (e.g. Acre, Brazil) or national (e.g. Guyana).

Leakage: The indirect impact and corresponding spatial shifting of an NbCS activity in one place and time on carbon storage in another place and/or time, which reduces the net effect of the intended intervention.

Methodology or Protocol: The rules that carbon crediting programs set for designing and implementing different kinds of carbon crediting projects. Each methodology includes eligibility criteria, methods for assessing emissions reduced or carbon removed, and methods for monitoring these reductions or removals for a specific project type or family of project types.

NbCS: Human actions that protect, better manage, and restore nature for climate mitigation.

REDD+: A climate mitigation framework that stands for reducing emissions from deforestation and forest degradation and other activities to enhance forest carbon stocks, developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC).

Reforestation: Establishment of forests on land that was previously forested, but currently is not (e.g. due to historical land clearing).

Registry: An entity that issues carbon credits such as Verra, the American Carbon Registry, the Climate Action Reserve, or Gold Standard.

Reversal: A reversal occurs when credited carbon that is stored outside the atmosphere is emitted or committed to be emitted to the atmosphere (e.g. when a tree dies from drought or fire). Carbon crediting programs often distinguish between avoidable reversals (such as elective decisions to harvest timber) from unavoidable reversals (such as a wildfire caused by lightning).

Voluntary carbon market: A market for trading carbon credits typically established and run by a non-governmental body, traditionally developed to help carbon credit buyers achieve voluntary emissions reduction goals.

-- END BOX --

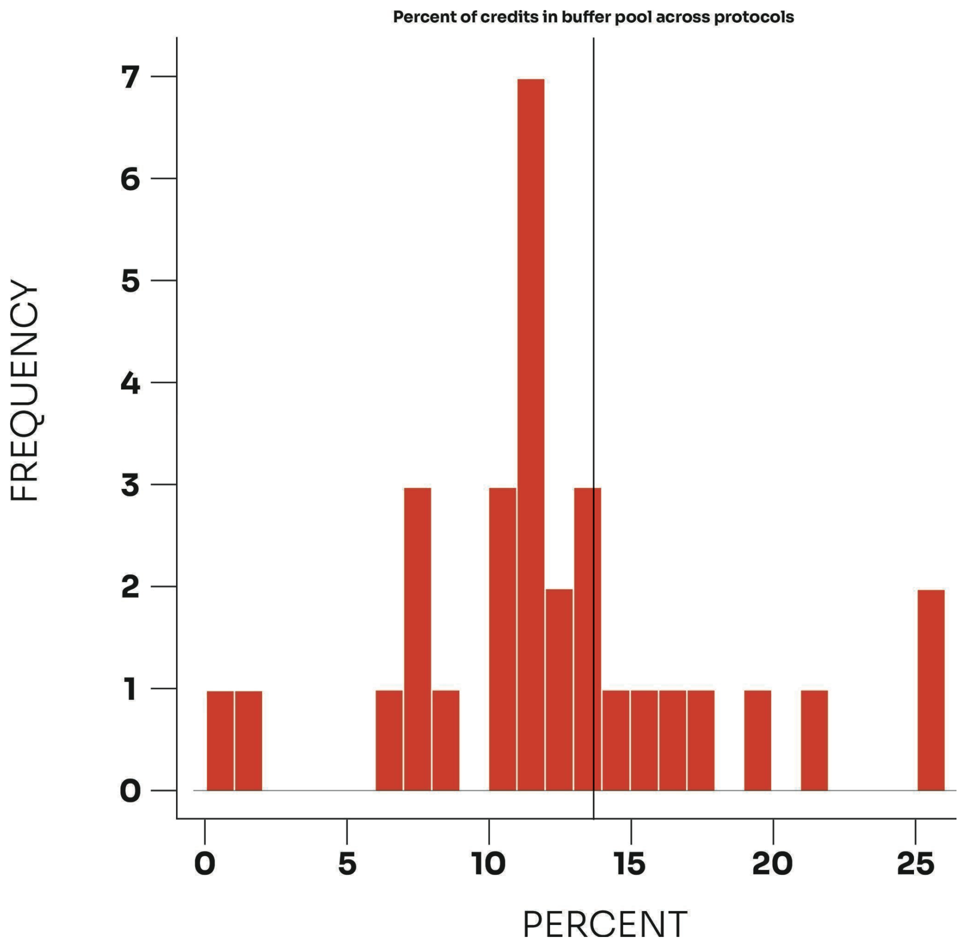

Figure S1: Buffer pool total sizes as a percentage of credits issued across currently active protocols in the voluntary carbon market as of December 2023. Black line is the credit-weighted average across protocols.

Supplementary Tables

Current Problem	**Immediate Solutions**	**Near-Term Solutions and Research Needs**
Net Climate Impact - No NbCS efforts to date account for the total climate impact of a given intervention - Changes in albedo may weaken or reverse climate benefits of reforestation or avoided deforestation efforts in some regions	Voluntary carbon registries and compliance market bodies should: - Incorporate albedo in NbCS carbon crediting protocols, and consider it in protocols for interventions and initiatives where albedo change is likely high (**Data**: Ref 38) - Disallow projects in places where albedo change outweighs the carbon storage benefit and fractionally reduce estimated climate benefits based on albedo changes	- Models and maps of the net climate impacts of a change in forests on cloud feedbacks, VOC and aerosol effects on climate, including direction and relative importance of different processes - Hydrologic cycle feedbacks (e.g. evapotranspiration) quantified and included in net climate impact maps
Durability - Most NbCS efforts do not base durability risks (e.g. buffer pool size) on robust, independent, spatially-varying data on natural and social risks - The role of climate change in increasing durability risks is rarely considered - Durability commitment is often far shorter (e.g. 20-40 years) than that needed for realizing climate mitigation benefits (>70-100 years) - Physical incommensurability of temporary forest carbon compared to fossil fuel carbon	Voluntary carbon registries and compliance market bodies should: - Update buffer pool contributions used by major forest NbCS efforts to reflect the current science (**Data**: Refs 61-62) - Use independent durability risk maps instead of projects selecting their own risk levels. - Strive for at least a 100 year lifetime in protocols - Allow durability mitigation to reduce buffer pool contributions only when based on empirical, region-, and intervention-specific science Carbon credit buyers should consider: - Durability of carbon storage needs to match the claim being made. Contribution claims could play a role	- Open-source tools to allow protocols and projects to extract their durability risk profiles for a given region, point, or project - Data-constrained and spatially-explicit estimates of the social risks to forest projects - Better inclusion of climate trends into durability risks and higher specificity for the risks by species or forest type - Syntheses on which management actions influence disturbance risk by biomes and regions - Liability could be transferred to the buyer of the carbon credit in the case of a reversal
Additionality - Extensive additionality and baseline problems in many NbCS protocols have led to widespread over-crediting - Little additionality has	Voluntary carbon registries and compliance market bodies should: - Shift to dynamic baselines where feasible - Improve jurisdictional baselines, which should be based on the best-available, consistent,	- Improvements in remote-sensing and ground measurements to map carbon stocks and fluxes at high resolution - Development of accurate and dynamic maps of past,

Current Problem	Immediate Solutions	Near-Term Solutions and Research Needs
been observed post hoc in most analyses to date	transparent, and independently-derived estimates of future forest loss and forest management Registries and carbon credit buyers should: - Increase transparency of baselines	current, and projected future management practices for additionality tools
Leakage - Leakage estimates in most NbCS protocols are too coarse and likely underestimated - Robust calculation of both activity and market leakage are exceptionally challenging to do currently	Voluntary carbon registries and compliance market bodies should: - Base leakage zones upon independently developed, third-party data and tools - More rigorously quantify leakage mitigation activities and not assume that activities eliminate all/most leakage - Require a market leakage deduction and account for international market leakage when a project reduced production of a commodity - Update leakage rates to conservatively reflect rates documented in the literature	- Maps and time-series datasets to distinguish the drivers (natural and human-driven) of forest loss over a region - Fusion of forest economic and land-use models with remote-sensing data to yield extensively-validated regional leakage rates - Shift to focus on projects where the climate benefits are unlikely to be undone by leakage
Structural challenges - Low transparency of direct emissions reductions vs carbon credits - Low transparency of climate benefit calculations - Lack of independence of verifiers creates potential conflicts of interest - Offsets and ton-for-ton accounting incentivize a 'race to the bottom' - Increasing legal risks to buyers of low-quality offsets	Policy-makers should: - Require separate disclosure of organization's direct emissions reductions and carbon credits used - Require transparency of critical data for recreating NbCS project climate benefits, including geographic boundaries, and baselines Voluntary carbon registries and compliance market bodies should: - Restructure verification process to financially decouple verifiers from project developers Carbon credit buyers should: - Expand funding models to include money-for-ton and money-for-money approaches	- Policy needed to require improved transparency - Further implement and test alternate claiming mechanisms, including a contribution approach to NbCS - Fund independent assessment of program effectiveness and dataset/tool development and updates

Table S1: Outline of steps towards more rigorous NbCS in forests with current problems, immediate solutions, and near-term solutions and research needs in each of the four components of rigor and structural challenges.

Registry	Minimum Lifetime	Project Type/ Activities	Methodology/Protocol	N Reg Proj	Issued Credits to 12-2023
ACR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	4	7891272
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	55	120182254
ACR Voluntary	40	ARR	AR-ACM0001: Afforestation and Reforestation of Degraded Land	2	6285796
		IFM	Improved Forest Management (IFM) on Non-Federal U.S. Forestlands	71	21290376
CAR-ARB	100	AC	ARB Compliance Offset Protocol: U.S. Forest Projects	1	244767
		IFM	ARB Compliance Offset Protocol: U.S. Forest Projects	70	74329960
CAR-Mexico	30	Forestry - MX	Mexico Forestry Protocol	150	3882275
CAR Voluntary	100	AC	U.S. Forest Protocol	5	1434257
		Conservation	U.S. Forest Protocol	2	464044
		IFM	U.S. Forest Protocol	17	8914408
GS	30	A/R	Afforestation/Reforestation GHG Emissions Reduction & Sequestration Methodology	23	5276349
Verra	20	ARR	AR-ACM0001: Afforestation and reforestation of degraded land	9	18547279
			AR-ACM0002: Afforestation or reforestation of degraded land without displacement of pre-project activities	1	58122
			AR-ACM0003 Afforestation and reforestation of lands except wetlands	41	12125521
			AR-AM0003: Afforestation and reforestation of degraded land through tree planting, assisted natural regeneration and control of animal grazing	1	42625
			AR-AM0005: Afforestation and reforestation project activities implemented for industrial and/or commercial uses	1	753975
			AR-AM0014: Afforestation and reforestation of degraded mangrove habitats	5	1678419
			AR-AMS0001: Simplified baseline and monitoring methodologies for small-scale A/R CDM project activities implemented on grasslands or croplands with limited displacement of pre-project activities	10	1782813
			AR-AMS0005: Simplified baseline and monitoring methodology for small-scale afforestation and reforestation project activities under the clean development mechanism…	1	78003
			AR-AMS0007: Afforestation and reforestation project activities implemented on non-wetlands	2	177917
		IFM	VM0003 Methodology for Improved Forest Management through Extension of Rotation Age	2	347696
			VM0005 Methodology for Conversion of Low-Productive Forest to High-Productive Forest	2	522431
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	11	5638882
			VM0011 Methodology for Calculating GHG Benefits from Preventing Planned Degradation	1	182347
			VM0012 Improved Forest Management in Temperate and Boreal Forests (LtPF)	5	5876946
		REDD	VM0004 Methodology for Avoided Planned Land Use Conversion in Peat Swamp Forests	1	33625616
			VM0006 Methodology for Carbon Accounting for Mosaic and Landscape-scale REDD Projects	3	7592929
			VM0007 REDD+ Methodology Framework	26	135341480
			VM0009 Methodology for Avoided Ecosystem Conversion	8	68125930
			VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest	2	241539
			VM0015 Methodology for Avoided Unplanned Deforestation	20	56477932

Table S2: Forest NbCS carbon credits issued as of December 2023 by registry, project type, protocol, and minimum required project lifetime.