Perspective

Towards more effective nature-based climate solutions in global forests

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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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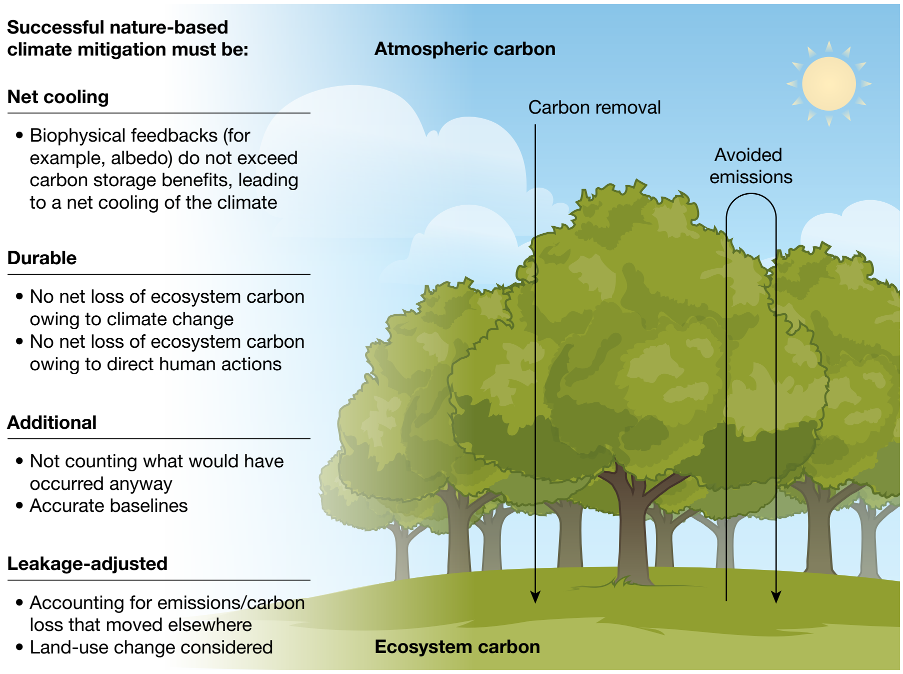

Fig. 1 | Key criteria for effective climate mitigation in forests. Central pathways of avoided emissions and carbon removal and four central criteria for rigorous and effective climate mitigation in NbCS in forests. We note that 'No net loss of ecosystem carbon' under the 'Durable' category means losses 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

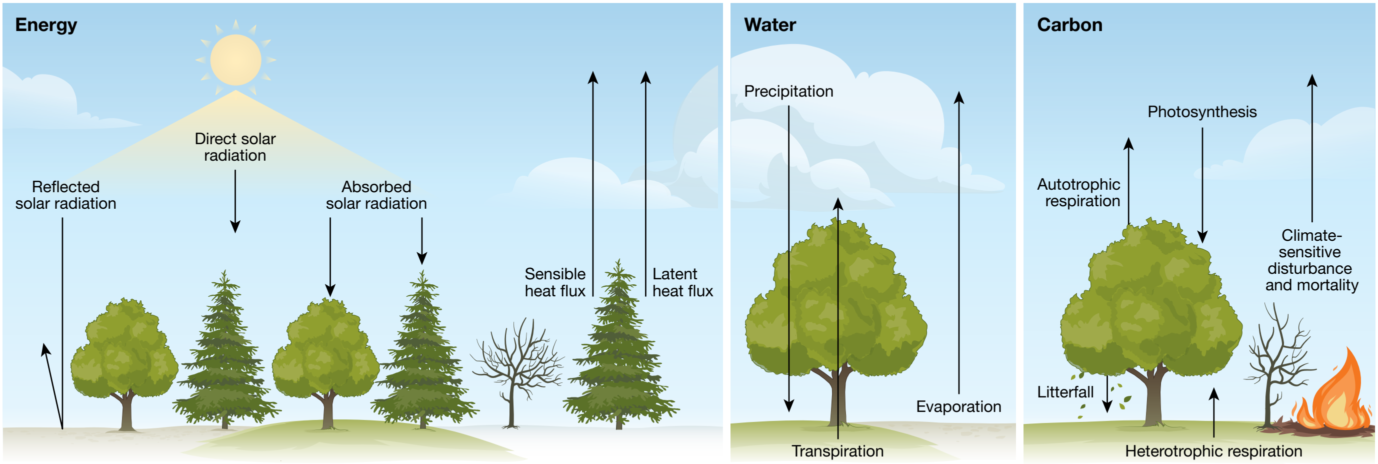

Fig. 2 | Key fluxes that mediate climate benefits of forests. Illustration of multiple key land–atmosphere interactions that mediate net climate impacts in energy, water and carbon cycles. Additional relevant feedbacks around clouds and circulation are not shown here.

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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