Environmental Science Advances

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

View Article Online
View Journal | View Issue

Cite this: *Environ. Sci.: Adv.*, 2025, **4**, 705

Reframing forest-based climate actions

Fuming Zhao,[a] Yueqin Shen[a] and Runsheng Yin *[b]

Forests are a crucial component in the international efforts toward mitigating climate change. Achieving the potential contribution of forest climate actions, however, is challenging. Just as the technical issues like monitoring and MRV (measurement, reporting, and verification) must be addressed, the institutional issues of fulfilling the emission reduction and removal (ER&R) responsibility, including climate governance and finance, must be worked out. Compared to the broad attention that the technical issues have attracted, however, fewer studies have explored the institutional issues. This article presents our perspective on how to tackle the institutional and technical issues coherently by asserting that it is paramount to build a more balanced portfolio of knowledge base and policy response. In addition to raising their climate ambitions, countries should consolidate their approaches to climate governance and nest local initiatives within the jurisdictional programs. They should also strengthen their means and measures for carrying out their commitments, including implementing more effective ER&R plans and enhancing carbon pricing mechanisms and public and private partnerships of climate investment. Thus, more research should be done on the comparative performance of alternative approaches to climate governance and nesting, and adopting more transparent standards, protocols, and methodologies. Further, greater attention should be directed to the longer-term, multi-dimensional effects of forest interventions with more reliable data and more robust techniques. Other than pursuing actions of the large, non-RBP (results-based payments) space, future research needs to examine not only the "results" but also the "payments" of RBP interventions.

Received 9th October 2024
Accepted 25th February 2025

DOI: 10.1039/d4va00361f

rsc.li/esadvances

Environmental significance

Forests are a crucial component in the international efforts toward mitigating climate change. Achieving the potential contribution of forest climate actions, however, is difficult. Just as the technical issues like monitoring and MRV (measurement, reporting, and verification) must be addressed, the institutional issues of fulfilling the emission reduction and removal (ER&R) responsibility must be worked out. Compared to the broad attention that the technical issues have attracted, fewer studies have addressed the institutional issues. This article offers our perspective on how to tackle the institutional and technical issues in an integrated manner.

Introduction

Forests are a crucial component in the international efforts of fighting climate change. As stressed by IPCC,[1] limiting global warming to 1.5 °C or well below 2 °C requires land-based mitigation, with most of the likely pathways including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy. When adopting the Glasgow Declaration at the 26th Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2021, world leaders promised to strengthen their shared commitments to conserve forest and other terrestrial ecosystems and accelerate their restoration, as well as to facilitate sustainable trade and development policies internationally and domestically.[2] However, sorting out and achieving the potential contribution of these forest sector climate actions, or nature-based solutions (NbSs), is complicated and challenging.[3,4] Hence, it is important and beneficial to tackle the relevant issues.

There exist technical issues on the monitoring and MRV (*i.e.*, measurement, reporting, and verification) of emission reduction and removal (ER&R) to be addressed, in addition to making future projections at the nexus of energy use, economic growth, and environmental change.[5] Likewise, there are institutional issues on assuming and fulfilling the ER&R responsibility to be worked out by the global community. Chief among the institutional issues are what appropriate governance approaches—jurisdictional or project oriented—to climate actions should be taken and how countries can finance the implementation of their actions to achieve the Paris climate targets.[6] Furthermore,

[a]*College of Economics and Management, Zhejiang A & F University, Hangzhou 311300, China. E-mail: psyboss@qq.com; shenyueqin@zafu.edu.cn*
[b]*Department of Forestry, Michigan State University, East Lansing, MI 48824, USA. E-mail: yinr@msu.edu*

these technical and institutional issues tend to be intertwined and thus must be tackled together.

Compared to the broad attention that the technical issues have attracted, nonetheless, fewer attempts have been made to address the institutional issues. Without careful exploration and resolution of the latter, however, it is less likely to advance the forest sector climate actions at scale. Therefore, a timely reframing of the forest sector climate actions is called for. This short essay offers our perspective on the subject by tackling the institutional and technical issues in a coherent manner. To that end, we examine, in the following sections, the changed role of the forest sector, the reality of financing forest sector actions, the rules of the forest carbon "game," the status of current research, and the recommendations to realign strategies and strengthen policies. We hope that our deliberations will help clarify the confusion and controversy surrounding the governance and implementation of forest sector climate actions and contribute to moving the international climate agenda forward.

Changed role of the sector

Forest sector NbSs were initially brought onto the international arena of climate change mitigation under the Clean Development Mechanism of the 1997 Kyoto Protocol, albeit with only afforestation and reforestation (A/R) being included.[7] While projects were carried out with support from some advanced economies (*i.e.*, Europe plus New Zealand), their coverage and scale was limited and carbon sequestration and storage was inconsequential. Later, the Bali Action Plan was adopted at the 2007 COP to reduce greenhouse gas emissions from deforestation and forest degradation (*i.e.*, REDD). In 2010, the COP decision on REDD+ expanded the role of forests in mitigating climate change to include conservation of forests, improvement of forest management, and enhancement of forest carbon stocks as well.[8]

The REDD+ initiative was envisioned to be a voluntary, national program in the pan-tropical, developing countries with financing from developed countries; however, it has been implemented as a mixture of national (and subnational) programs and individual projects.[7] The UNFCCC's encouragement for "demonstration activities," coupled with the perceived profitable opportunities, prompted an early explosion of local REDD+ projects in the voluntary carbon markets.[9] The first private project was launched in 2008 in Colombia,[10] and Brazil was the first country to submit its national forest reference level, or FRL, to the UNFCCC in 2014.[8] After completing the required action plan and other tasks, Brazil was, again, the first to receive results-based payments (RBP) from the Green Climate Fund (GCF)—an operating arm of the financial mechanism under the UNFCCC—in 2019.

Last several years have witnessed an increased interest in and rapid growth of forest-based ER&R and carbon offsetting, as more and more business and other social organizations have made their pledges to reach carbon neutrality before the mid-century.[11] But the RBP transactions have been slow coming and thus unable to deliver the expected impact as promoted by some advocates, which we will discuss later. More importantly, the passage of the Paris Agreement invalidated the bifurcation between Annex I (developed) countries and non-Annex I (developing) ones in allocating and assuming the ER&R responsibility. Every country, or Party, has been mandated to submit its nationally determined contribution (NDC) to the UNFCCC, and close to 70% of them included forest sector actions in their initial NDCs. With a heightened alert of the climate crisis and improved knowledge of forest sector's mitigation potential, countries, especially the large emitters, have been urged to raise their climate ambitions. By 2020, 90% of the Parties incorporated Land Use, Land-Use Change and Forestry (LULUCF) actions in their NDCs. In comparison, about 60 developing countries have reported REDD+ activities, mostly readiness and piloting, to the UN Climate Change Secretariat.[12]

According to Griscom *et al.*,[3] forest-based pathways offer over two thirds of cost-effective NbSs needed to hold warming to below 2 °C and about half of low-cost mitigation options. More specifically, reforestation is the largest natural pathway and avoided forest conversion offers the second largest maximum and cost-effective mitigation potential. Improved forest management, or IFM (*i.e.*, natural forest management and improved plantations pathways), possesses large, cost-effective mitigation opportunities. Together, the LULUCF actions would more than double the ER&R effects of the REDD+ initiative to over 10 billion tons of carbon dioxide equivalent (or tCO_2e) a year if they could be adequately adopted.[3,13] Moreover, it is agreed that most, if not all, of the LULUCF actions are more effective in terms of both cost and time compared to many other ER&R alternatives, particularly in such sectors of the economy as energy, manufacturing, and transportation.

As a matter of fact, the small, local REDD+ projects themselves have begun to shift toward jurisdictional regimes,[14] which is thought to be crucial to the successful execution of NbSs at the national level.[11,15] A jurisdictional REDD+ program is a government-led endeavor to address the drivers of deforestation and forest degradation and to enhance forest carbon stock over a large national (or subnational) jurisdiction. It differs from individual projects, which cover a relatively small area, undertake activities (as opposed to policies and regulations) to address local drivers of deforestation and forest degradation and are often carried out by civil society organizations and private companies.[11]

In short, REDD+ is no longer inclusive of the ER&R efforts that the world forest sector is expected to undertake, with the latter necessary for achieving the Paris climate targets, along with sustainable development, being far beyond the scope and significance of the former. Therefore, it is paramount to view the evolution of forest sector NbSs in this broader context to seek more effective governance approaches and means and measures to advance the global climate agenda.

Reality of financing

In principle, developing countries achieving REDD+ results could be awarded RBPs, which may come from multiple sources, including the GCF, the Carbon Fund of the World Bank Forest Carbon Partnership Facility (FCPF), and bilateral and

multilateral international assistance. In addition, voluntary and compliance carbon markets and other jurisdictional and philanthropic funding sources have become more and more significant in support of domestic and international climate initiatives.

A pilot program for RBPs was launched by the GCF in 2017. Since 2019, it has approved the REDD+ RBP funding proposals of eight countries, offering a total of 133 million tCO_2e. Unfortunately, its envelope was depleted in 2020 and a subsequent phase has been part of the ongoing international negotiations. According to Sandker *et al.*,[16] as of September 2022, 56 countries had submitted 75 reference levels and 18 of them reported REDD+ results, and 386 million tCO_2e of REDD+ results had been awarded RBPs for results achieved between 2006 and 2016 in seven of the eight countries. Likewise, since 2020, seven countries have reported REDD+ results to the FCPF Carbon Fund, with six of the available reports having a combined ER&R of 104 million tCO_2e. The first RBP under Carbon Fund was made at the end of 2021. Overall, the World Bank[17] indicates that its FCPF has supported 47 countries in their piloting and implementation of the REDD+ programs/projects with an annual budget of a few hundred of million dollars. The RBP transactions handled by the GCF and the FCPF have so far been uniformly priced at just \$5 per tCO_2e.[16]

For one reason of the limited international climate finance, developed countries have failed to deliver what they promised in 2009—US\$100 billion a year by 2020—to aid mitigation and adaptation actions in developing nations.[18] A large portion of that pledge (~US\$10–15 billion per year) was intended to cover expenses on preparing and executing REDD+ actions.[19] Consequently, the GCF and the FCPF have run into continued funding constraints, and the intergovernmental climate finance is reflected in just a few large bilateral and multilateral agreements.[8]

Furthermore, while active and rapidly evolving, voluntary carbon markets, including trading activities in the LULUCF arena, represent a small portion of the existing, let alone the expected, size of global carbon markets. The trade volume of forest carbon credits in the voluntary markets peaked at 517 million tCO_2e in 2021, but it dropped to less than one tenth of that amount in 2023,[20] largely due to the credits' perceived lack of credibility.[21] Additionally, forest carbon credits have accessed compliance markets in only a few national (*e.g.*, New Zealand and China) and subnational (*e.g.*, California and Quebec) jurisdictions, with a very low range of allowable offsets (<8%). Of course, these unpleasant developments have to do with the fact that it takes time and effort to resolve the challenges encountered in determining the reference levels and thus carbon additionalities of REDD+ and other forest projects or programs.[16]

Meanwhile, jurisdictional funding has become essential in advancing A/R, IFM, and other forest sector actions by expanding public sector forest finance and leveraging sovereign and philanthropic funding to mobilize more private capital.[11] To deal with the limited capability and inefficiency associated with the project-oriented approach and to accelerate the pace of climate mitigation and adaptation, governments, businesses, and other entities have increasingly engaged in carbon financing through jurisdictional approaches. Organizations that wish to reduce emissions *via* REDD or to enhance removals *via* A/R or IFM finance forest sector NbSs across an entire jurisdiction, instead for individual projects. The resulting payments are made to the jurisdictional authorities where the NbSs are pursued. In fact, as a core component of the climate governance paradigm under the Paris Agreement, jurisdictional funding represents an important turning point in carbon financing.[22] Many countries, such as India and Canada, have launched their tree-planting, forest management, or biomass utilization initiatives. Countries have also undertaken ecological restoration programs (ERPs) as part of their commitments to sustainable development.[13] While most of the ERPs may not have been originally conceived for carbon sequestration or emission offsetting, they are now called upon to serve this additional function.[5] Following the UN declaration of this decade as the Decade of Ecosystem Restoration, ERPs have become a primary platform for funding ER&R activities in the forest sector.[13]

China is a case in point. The central government already invested about 700 billion yuan (\$110 billion) by 2017 in several large ERPs.[23] Also, the country has planned to spend about three trillion yuan (\$470 billion) on nine large regional ecosystem restoration and conservation initiatives during 2021–2035, which are expected to further improve the ecological conditions and the local people's livelihoods. When these programs were originally planned, carbon sequestration and storage by forest and other terrestrial ecosystems was not explicitly considered. With the country's updated NDC targets to peak GHG emissions this decade and reach carbon neutrality before 2060, however, they have attracted broad interest for removing carbon from the atmosphere to offset its emissions.[24]

Another recent positive development is that COP29 was able to bring together nearly 200 countries in Baku, Azerbaijan, and reach a breakthrough agreement with a central focus on climate finance.[25] Included in the agreement are: (1) triple finance to developing countries, from the previous goal of USD 100 billion annually to USD 300 billion annually by 2035; and (2) secure efforts of all actors to work together to scale up finance to developing countries, from public and private sources to the amount of \$1.3 trillion per year by 2035. To accomplish these international funding goals while accelerating domestic climate support, it is crucial to realign our strategies of governing and implementing climate actions, including those in the forest sector.

Rules of the carbon "game"

The UNFCCC has always focused on the key role that national authorities play in mitigating climate change.[5] For the REDD+ initiative, countries were required to develop, in addition to an action plan and FRLs, a forest monitoring system and a safeguards information system.[7] However, the early actions through individual projects gave rise to a myriad of local challenges such as meeting accounting requirements, assuring buyer confidence, and securing community rights, among others.[26] In comparison, the NDC architecture of the Paris Agreement

underpins jurisdictional approaches to climate governance—making and executing pledges by administrative bodies of a national authority, with the obligations of subordinate bodies being nested within the national pledge.[26,27] Meanwhile, the UNFCCC and its supreme governing body, the COP, track the progress that has been made by a given Party and assess to what extent the pledged commitments by all Parties will collectively meet the global temperature targets.[2] Brazil's persistent reduction of deforestation during the first 16 years of this century[28] and China's substantial expansion of forest cover over the last several decades[24] are examples of successful jurisdictional endeavors.

Governance is the process of making and enforcing decisions within an organization (society).[29] Adopting jurisdictional approaches has made what we learned under the Kyoto Protocol or from the experience of forest carbon markets inadequate. So, it is imperative to expand our perspective of and realign the policy and practice in governing forest sector climate actions,[6,24] which we argue is far more than "effective regulation" itself.[30] Nesting pertains to how governments mobilize, coordinate, and supervise subnational, often local and smaller-scale, activities, and integrate them with larger national programs to achieve their NDCs and support the transition to low-carbon development.[14] It entails not only the design and execution of national and subnational activities but also the identification and verification of their baselines or FRLs, against which the intervention outcomes can be determined.[31,32]

Of course, the primary outcome of any intervention is its carbon additionality—whether and to what extent it reduces emissions from deforestation and forest degradation or increases emission removals from A/R, IFM, and other actions. This additionality is also linked to carbon leakage avoidance—whether emission reductions in one place are displaced by those to another place—and permanence—whether the benefits of emission reductions are reversed.[21] Without taking these requirements and rules into account of the MRV process, the assessed additionality can easily be called into question, and concerns about the credibility and accountability of forest carbon projects will ensue.

Further, there exist multiple distinctions between RBP and non-RBP climate solutions. First, the baselines differ. For REDD+ and other RBP projects, the baselines for carbon emission reductions are the emission levels under the business-as-usual scenario.[19,31] These baselines are set for a given period, over which the annual emission levels may vary. Carbon additionality is the yearly difference between the actual emission and the emission corresponding to the FRL. In contrast, for non-RBP cases, forest sector climate actions are compared with reference to a single base year. Total emissions reduced and removed in that base year are subtracted from those in the future accounting period to determine the number of credits or debits resulting from the identified activities.[2] For comparison, China uses 2005 as its base year, whereas REDD+ projects in Brazil have no single base year but must develop the historical trajectory over a period (say, 2016–2020) according to their counterfactuals of no intervention.[4] Offsetting and crediting practices are different as well. REDD+ actions are driven by international finance, and project funding from various sources has been slow and small. For non-REDD+ countries, most transactions and finances are domestic, with expenses to be covered by revenues from a carbon pricing mechanism or with public or private finance. This distinction is relevant as more countries develop their own programs of forest carbon or ecosystem restoration through jurisdictional financing.[4] In general, the above distinctions have direct implications to the governance and finance of climate solutions.

Moreover, compared to project-based approaches, jurisdictional ones tend to have certain advantages beyond their conformity with the NDC architecture.[11,26] As elaborated elsewhere,[4,26] jurisdictions have stronger capabilities of monitoring and MRV in carrying out their commitments. That is, accounting and offsetting across multiple projects within a large region or country can alleviate the more uncertain but less permanent outcomes of time-limited activities to ensure the accuracy and reliability of forest carbon additionality and credits. Also, jurisdictional approaches make it more practical for the ER&R safeguards to be more adequately fulfilled, and they can be more efficient as the entry barriers for smallholders and the high transaction costs and uncertainties are alleviated over larger spatial coverage. As a result, they are expected to lead to a greater likelihood for countries to accomplish the necessary climate actions. Jurisdictional funding has also opened new opportunities for "nesting" and "hybridizing" market-based, public, and other private alternatives; as such, it promises to accelerate funding of forest sector NbSs.[33] For example, unlike project developers, governments have the authority to enforce policy and control land use change broadly, while the private sector can serve as a source of immediate RBPs. Also, incentives for aggregating projects across a jurisdiction can mitigate the risks of non-additionality, non-permanence, and leakage, and the threats to indigenous rights.[22,26]

On the other hand, while individual carbon projects feature "bottom-up" initiatives and direct linkages to local interest and participation, some of their weaknesses, such as the limited capacity and coordination, and the lack of accountability as well as credibility, have been unfolding.[34,35] In fact, numerous rainforest carbon offsets by some of the biggest certifiers have been found to be worthless.[36] Of course, jurisdictional approaches face their own challenges as well. Among others, they may be insufficiently transparent or flexible, subject to corruption and political turnover, and/or lack of broader support and incentives;[33] coordination across scales in these projects generates challenges vertically across spatial and jurisdictional scales, but also horizontally across sectors.[1] Thus, the differences between RBP and non-RBP actions of the forest sector and the advantages and disadvantages of alternative approaches to governing forest sector actions must be better understood for purposes of climate policy design and implementation.

Status of the current research

Many scholars have heeded the conditionalities of forest carbon interventions, including baseline identification, leakage detection, and permanence assessment. For instance, Mertz *et al.*[37]

and Teo *et al.*[32] investigated the uncertainties in establishing FRLs and predicting future carbon stocks. Highlighting the variability of local forest conditions and thus the difficulty of determining carbon additionality, they argued for scaling up project implementation and assessment to a higher level of aggregation. In examining carbon leakage, for instance, Steck[38] made the case for integrating avoided deforestation projects into national REDD+ strategies and underscored the need for nesting. Galik *et al.*[39] revealed non-permanence in A/R projects under the CDM and explored options for addressing them. Sun *et al.*[40] further demonstrated that if the permanence condition is ignored, the forest carbon credits generated can be inevitably exaggerated.

Nonetheless, limited attempts have been made to investigate how to scale up forest climate interventions, what the comparative advantages and disadvantages of alternative governance approaches, as well as their differentiated capabilities and complex linkages, are, and how to nest local carbon projects into jurisdictional climate programs. On the other hand, evaluating the impacts of forest sector interventions, including projects linked to the voluntary markets, has been a hot topic. While some of these evaluations were based on randomized controlled experiments (RCE), such as Jayachandran *et al.*,[41] many are observational studies (OBS), such as West *et al.*,[10,42] Groom *et al.*,[19] and Roopsind *et al.*[31]

Jayachandran *et al.*[41] assessed a popular intervention—financial incentives for small landowners to keep their forests intact—in Uganda. They reported that the program caused an increase in tree cover of 5.55 ha per village, and the cost of the two-year trial was $0.46 per averted ton of CO_2. By randomly assigning who would be eligible for the program, this type of work is not subject to concerns about biased estimates due to self-selection into the program or targeting by program administrators based on unobservables.[43] Also, it is advantageous for the study to use high-resolution satellite images in detecting tree cuttings. Because an RCE can be costly and get into ethical and other problems,[43] however, its application remains rare.

West *et al.*[42] claimed overstated emission reductions by most of the REDD+ projects in Brazil, and a similar finding for several other countries was reported by West *et al.*[10] Groom *et al.*[19] and Roopsind *et al.*[31] are analyses of national jurisdictions; the former echoed the earlier finding for Indonesia, whereas the latter indicated that the program of Ecuador was successful. Another two studies[44,45] dealt with carbon offsetting under California's cap and trade program, showing a "systematic over-crediting" due to inaccurate FRLs. Identifying a counterfactual in determining the impact of a RBP intervention, nonetheless, is not easy given the impracticality of assigning the treatment randomly and the existence of confounding factors. An added difficulty is that at the national level, it is hard to find a comparison group, leading to the creation of a synthetic control.[46] However, each unit in the donor pool must be chosen judiciously to provide a reasonable control for the treated unit, and this, plus the decisions on predictor selection and durations of model fitting before validation and prediction post validation, could alter the assessed outcomes somewhat.[32,37]

Notably, West *et al.*[10,42] knew that the REDD+ projects were not part of the NDCs of those covered countries, and that the voluntary markets seemed lack of integrity. So, they suggested an alignment of project- and national-level carbon accounting, and they further asserted that imposing one common baseline would in turn facilitate the inclusion of emission reductions claimed by decentralized initiatives into national GHG emission inventories. These steps would ultimately ensure consistency in the treatment of leakages and avoid ER&R double-counting. Likewise, Badgley *et al.*[44] and Coffield *et al.*[45] highlighted the challenges of quantifying carbon additionality and called for improving program design and offsetting protocol. Also worth noting is that most of the evaluations used geospatial data of forest cover derived from satellite imagery. The use of high-resolution satellite images can generate accurate and continuous observations that may not come from a forest inventory system due to its focus on aggregate units and infrequent iteration (in every 5–10 years). If the spatial resolution is coarse (say, one pixel covers at least 1 km × 1 km) like that of Roopsind *et al.*[31] and Groom *et al.*,[19] however, the data may not have the precision that a quality impact evaluation requires.[41] It is unclear whether and under what circumstances and standards the geospatial data are permissible as a substitute for forest inventory information in carbon accounting and offsetting.

Closing remarks

Tremendous progress has been made in piloting, executing, and evaluating forest sector NbSs, especially RBP interventions like REDD+. As our knowledge of the climate crisis and the global commitment necessary to tackle it deepen, the forest sector has seen a greatly expanded set of actions to mitigate and adapt to climate change. Meanwhile, adopting the Paris climate targets and implementing the NDC-centered means and measures has made what we learned under the Kyoto Protocol or from the experience of voluntary markets less useful. Still, recent policy and research endeavors have been largely concentrated on such technical matters as monitoring, MRV, baselining, and projection. Except for issues pertaining to impact evaluation, scant attention has been devoted to the institutional matters encountered in carrying out the envisioned climate actions. As a result, barriers abound in the design of policies, institutions, and governance systems at all scales that will contribute to land-related mitigation while facilitating the pursuit of climate-adaptive development pathways.[1]

Going forward, therefore, it is essential to build a more balanced, relevant knowledge base and to seek more sensible, effective policy options, which means a reframing of the forest sector actions and a reprioritization of the global climate agenda. First of all, we must recognize that the ER&R efforts that the world forest sector is expected to undertake for achieving the Paris climate targets are much larger, broader, and more important that REDD+.[13] Therefore, all forest sector NbSs deserve adequate and consistent ER&R attention.

Second, in addition to raising their climate ambitions, Parties must strengthen their means and measures for carrying out their commitments, including developing and implementing more effective action plans and enhancing carbon pricing and other market mechanisms, and public and private climate financing. The bilateral and multilateral climate finance and other international funding channels must also be strengthened in terms of availability and access. It is especially crucial to design equitable and effective RBP schemes and improve the fairness, transparency, and accountability of allocating and using climate funds at the local level.[30,33] Third, countries need to clarify and consolidate their approaches to climate governance and nest local initiatives and activities within the national programs appropriately. Just like a jurisdiction relies on implementing concrete projects to accomplish its climate commitment, the success of a project depends on how well it is integrated within a jurisdictional approach. Fourth, the UNFCCC and other international agencies should monitor the actions and track the progress of Parties more closely and effectively. In particular, the principles and practices of carbon accounting, offsetting, and safeguarding need to be more clearly and coherently specified and even standardized if possible.

Accordingly, more research should be conducted on the comparative performance of alternative approaches to climate governance and nesting, as well as on developing and adopting uniform protocols and methodologies. In this regard, first, greater efforts should be directed to the longer-term, multi-dimensional effects of forest sector interventions, REDD+ or otherwise, with more reliable data and more robust methods. Second, it is beneficial to clearly delineate the differences between RBP and non-RBP actions of the forest sector and the advantages and disadvantages of the alternative governance approaches in addition to their variable capabilities and linkages. Third, it is of keen interest to examine whether the notion of "keeping forests standing"[47] is universally justifiable for carbon sequestration and storage. While appealing and reasonable under certain circumstances, it may not stand up to scrutiny because of the increasing opportunity cost of holding a larger forest stock for a longer time combined with the demand for commercial use of wood at competitive revenues. Improving forest conditions should be done in close coordination with improving wood products processing and utilization, considering their feasibility and benefit of substituting for products derived from fossil fuel or non-renewable materials.

Finally, in addition to the large activities of the non-RBP space, future research needs to examine not only the "results" but also the "payments" of RBP interventions, including how to raise carbon prices closer to the social cost of carbon and how to integrate forest-based offsets into compliance and voluntary carbon markets more broadly and effectively. Meanwhile, it is essential to explore how countries expand the scope and increase the magnitude of their funding for climate actions from jurisdictional, philanthropic, and other sources. Hopefully, these steps will go a long way in advancing the forest sector NbSs and supporting the low-carbon, green transition of the world economy.[1,6]

Data availability

As a perspective piece, no original data were used in it and thus no need for data disclosure.

Author contributions

FMZ: conceptual formulation, data collection and processing, analysis, manuscript writing; YQS: conceptual formulation, data processing, manuscript writing and revision, coordination; RSY: conceptual formulation, data collection and processing, analysis, manuscript writing and revision.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors appreciate the constructive comments and criticisms made by the reviewers and editors of this journal, as well as many of their colleagues and students in the U.S. and China, most notably Bill Hyde, Ying Lin, and Wei Xie. R. S. is grateful for financial support from the AgBioResearch of Michigan State University.

References

1 IPCC (International Panel on Climate Change), Climate Change and Land: Summary for Policymakers, 2020, available at: **https://www.ipcc.ch/srccl/**.
2 UNFCCC (United Nations Framework Convention on Climate Change), *Reference Manual for the Enhanced Transparency Framework under the Paris Agreement*, Bonn, Germany, 2020.
3 B. W. Griscom, J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, *et al.* Natural climate solutions, *Proc. Natl. Acad. Sci. U.S.A.*, 2017, **114**(44), 11645–11650.
4 R. S. Yin, *Global Forest Carbon: Policy, Economics and Finance*, Routledge, UK, 2024.
5 IPCC (International Panel on Climate Change), Climate Change 2022: Impacts, Adaptation and Vulnerability, *Working Group II Contribution to the Sixth Assessment Report*, 2022.
6 W. Nordhaus, *The Spirit of Green*, Princeton University Press, New Jersey, 2021.
7 FAO (Food and Agriculture Organization of the United Nations), *Forestry for a Low-Carbon Future: Integrating Forests and Wood Products in Climate Change Strategies (FAO Forestry Paper 177)*, Rome, Italy, 2016.
8 *Forests, Climate, Biodiversity and People: Assessing a Decade of REDD+*, ed. Parrotta, J., Mansourian, S., Wildburger C. and Grima, N., IUFRO World Series, Vienna, 2022, vol. 40.
9 S. Wunder, A. E. Duchelle, Cd. Sassi, E. O. Sills, G. Simonet and W. D. Sunderlin, REDD+ in Theory and Practice: How Lessons from Local Projects Can Inform Jurisdictional

Approaches, *Front. For. Glob. Change*, 2020, **3**, 11, DOI: 10.3389/ffgc.2020.00011.

10 T. A. P. West, S. Wunder, E. O. Sills, J. Börner, S. W. Rifai, A. N. Neidermeier, G. P. Frey and A. Kontoleon, Action needed to make carbon offsets from forest conservation work for climate change mitigation, *Science*, 2023, **381**(6660), DOI: 10.1126/science.ade3535.

11 S. Donofrio, P. Maguire, K. Myers, C. Daley and K. Lin, *State of Forest Carbon Finance 2021*, Forest Trends Association, Washington DC, 2021.

12 UNFCCC (United Nations Framework Convention on Climate Change), What is the Kyoto Protocol?, 2023, available at: https://unfccc.int/kyoto_protocol.

13 S. Roe, C. Streck, M. Obersteiner, S. Frank, B. Griscom, L. Drouet, *et al.* Contribution of the land sector to a 1.5 °C world, *Nat. Clim. Change*, 2019, **9**, 817–828, DOI: 10.1038/s41558-019-0591-9.

14 UNFCCC (United Nations Framework Convention on Climate Change), Linking REDD+, the Paris Agreement, Nationally Determined Contributions and the Sustainable Development Goals: Realizing the Potential of Forests for NDC Enhancement and Implementation, 2022, Available at: https://www.un-redd.org/sites/default/files/2022-03/NDCFinal.pdf.

15 S. Irawana, T. Widiastomo, L. Tacconi, J. D. Watts and B. Steni, Exploring the design of jurisdictional REDD+: The case of Central Kalimantan, Indonesia, *For. Policy Econ.*, 2019, **108**, 101853.

16 M. Sandker, T. Neeff, K. Todd, A. Poultouchidou, R. Cóndor-Gólec, F. Felicani-Robles, L. Santos-Acuña and A. Duchelle, *From Reference Levels to Results: REDD+ Reporting by Countries – 2022 Update*, Forestry Working Paper No. 35, FAO, Rome, 2022, DOI: 10.4060/cc2899en.

17 World Bank, *Forest Carbon Partnership Facility Annual Report 2024*, Washington, DC, USA, 2024.

18 J. T. Roberts, R. Weikmans, S. Robinson, D. Ciplet, M. Khan and D. Falzon, Rebooting a failed promise of climate finance, *Nat. Clim. Change*, 2021, **11**, 180–182.

19 B. Groom, C. Palmer and L. Sileci, Carbon emissions reductions from Indonesia's moratorium on forest concessions are cost-effective yet contribute little to Paris pledges, *Proc. Natl. Acad. Sci. U.S.A.*, 2022, **119**(5), e2102613119.

20 S. Donofrio, C. Calderon, L. Weatherer and A. Procton, *Paying for Quality: State of the Voluntary Carbon Markets 2023*, Forest Trends Association, Washington DC, 2023.

21 A. Balmford, P. H. S. Brancalion, D. Coomes, B. Filewod, B. Groom, A. Guizar-Coutiño, J. P. G. Jones, S. Keshav, A. Kontoleon, *et al.* Credit credibility threatens forests, *Science*, 2023, **380**(6644), 466–467, DOI: 10.1126/science.adh3426.

22 Y. Wang, L. Li and R. S. Yin, A primer on forest carbon policy and economics under the Paris Agreement, *For. Policy Econ.*, 2021, **132**, 102595.

23 K. Zhou, D. Midkiff, R. S. Yin and H. Zhang, Carbon finance and funding for forest sector climate solutions: A synthesis of principles, mechanisms, and developments, *Front. Environ. Sci.*, 2024, DOI: 10.3389/fenvs.2024.1309885.

24 J. Y. Hou and R. S. Yin, How significant a role can China's forest sector play in decarbonizing its economy?, *Clim. Polic*, 2022, DOI: 10.1080/14693062.2022.2098229.

25 UNFCCC (United Nations Framework Convention on Climate Change), UN Climate Conference Agrees to Triple Finance to Developing Countries, Protecting Lives and Livelihoods, 2024, https://unfccc.int/cop29.

26 R. DeFries, R. Ahuja, J. Friedman, D. R. Gordon, S. P. Hamburg, S. Kerr, J. Mwangi, C. Nouwen and N. Pandit, Land management can contribute to net zero, *Science*, 2022, **376**(6598), 1163–1165.

27 M. Von Essen and E. F. Lambin, Jurisdictional approaches to sustainable resource use, *Front. Ecol. Environ.*, 2021, **19**(3), 159–167, DOI: 10.1002/fee.2299.

28 Global Forest Watch, Brazil's Deforestation, 2024, https://www.globalforestwatch.org/dashboards/country/BRA/.

29 E. Ostrom, Beyond markets and states: polycentric governance of complex economic systems, *Am. Econ. Rev.*, 2010, **100**, 641–672.

30 R. Pande, Fixing forest carbon credits, *Science*, 2024, **383**(6679), DOI: 10.1126/science.adn4923.

31 A. Roopsind, B. Sohngen and J. Brandt, Evidence that a national REDD+ program reduces tree cover loss and carbon emissions in a high forest cover, low deforestation country, *Proc. Natl. Acad. Sci. U.S.A.*, 2019, **116**(49), 24492–24499.

32 H. C. Teo, N. H. L. Tan, Q. Zheng, A. J. Y. Lim, R. Sreekar, X. Chen, Y. Zhou, T. V. Sarira, J. D. T. De Alban and H. Tang, Uncertainties in deforestation emission baseline methodologies and implications for carbon markets, *Nat. Commun.*, 2023, DOI: 10.1038/s41467-023-44127-9.

33 W. Boyd, C. Stickler, A. E. Duchelle, F. Seymour, D. Nepstad, *et al.*, *Jurisdictional Approaches to REDD+ and Low Emissions Development: Progress and Prospects*, World Resources Institute, Washington, DC, 2018.

34 G. Wells, U. Pascual, C. Stephenson and C. M. Ryan, Confronting deep uncertainty in the forest carbon industry, *Science*, 2022, **382**(6666), 41–43.

35 S. Zadek, *Trouble with Carbon Markets*, Project Syndicate (March 1), 2023.

36 P. Greenfield, Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows, *The Guardian*, 2023.

37 O. Mertz, K. Grogan, D. Pflugmacher, *et al.* Uncertainty in establishing forest reference levels and predicting future forest-based carbon stocks for REDD+, *J. Land Use Sci.*, 2018, **13**, 1–15.

38 C. Steck, REDD+ and leakage: debunking myths and promoting integrated solutions, *Clim. Polic*, 2021, **21**, 843–852.

39 C. Galik, B. C. Murray, S. Mitchell and P. Cottle, Alternative approaches for addressing non-permanence in carbon projects: an application to afforestation and reforestation under the Clean Development Mechanism, *Mitig. Adapt. Strateg. Glob. Chang.*, 2016, **21**, 101–118.

40 H. Y. Sun, D. Midkiff, R. S. Yin and X. P. Yuan, Different outcomes of alternative forest carbon accounting approaches at the local level, *PLOS Climate*, 2023, **2**(5), e0000191, DOI: **10.1371/journal.pclm.0000191**.

41 S. Jayachandran, J. de Laat, E. F. Lambin, C. Y. Stanton, R. Audy and N. E. Thomas, Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation, *Science*, 2017, **357**, 267–273.

42 T. A. P. West, J. Borner, E. O. Sills and A. Kontoleon, Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon, *Proc. Natl. Acad. Sci. U.S.A.*, 2020, **117**(39), 24188–24194.

43 S. Athey and G. W. Imbens, The state of applied econometrics: causality and policy evaluation, *J. Econ. Perspect.*, 2017, **31**(2), 3–32.

44 G. Badgley, J. Freeman, J. J. Hamman, B. Haya, A. T. Trugman, W. R. L. Anderegg and D. Cullenward, Systematic over-crediting in California's forest carbon offsets program, *Glob. Change Biol.*, 2022, **28**, 1433–1445, DOI: **10.1111/gcb.15943**.

45 S. R. Coffield, C. D. Vo, J. A. Wang, G. Badgley, *et al.* Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects, *Glob. Change Biol.*, 2022, **28**, 6789–6806, DOI: **10.1111/gcb.16380**.

46 A. Abadie, Using Synthetic Controls: Feasibility, Data Requirements, and Methodological Aspects, *J. Econ. Lit.*, 2021, **59**(2), 391–425.

47 Verra, Setting the Standard: Verra's Revolutionary New REDD Methodology, 2023, available at: **https://verra.org/program-notice/setting-the-standard-verras-revolutionary-new-redd-methodology/**.