



Identifying Research Priorities for the Development of High-Integrity Forest Carbon Credits

Chad C. Papa · Melissa Kreye · Evan Beresford · Sarah Widderich · William R. L. Anderegg · Ethan P. Belair, et al. *[full author details at the end of the article]*

Received: 2 March 2026 / Accepted: 13 August 2026
© The Author(s) 2026

Abstract

In the United States, voluntary carbon markets have gained significant traction in recent years. However, many offset standards, protocols, and credit ratings have come under scrutiny from the public and investors for failing to produce real or sustainable carbon offsets. Additionally, communities often find themselves unprepared to advocate for forest-based carbon projects that align with their needs and interests, mainly due to a lack of information and a general distrust surrounding carbon projects. There is a pressing need to address the social, ecological, and technological barriers that hinder the development of higher-integrity carbon credits and limit crucial financing for climate change mitigation activities. This paper is the culmination of findings from a series of discussions held in 2025 by leading academics, non-profit organizations, and forestry professionals to identify key challenges, research priorities, and actionable steps to scaling voluntary forest carbon markets. The discussions focused on six priority areas including permanence; additionality; leakage; measurement, monitoring, reporting, and verification (MMRV); market investments; and the social and ecological implications of carbon markets. By reporting on these discussions, we aim to strengthen conversations across forest carbon topics to enhance market access while simultaneously identifying needs for developing high-integrity forest carbon projects for climate change mitigation and rural communities.

Keywords Voluntary carbon markets · Forest carbon offsets · High-integrity carbon credits · Natural climate solutions · Forest carbon

Growing Demand for High-Integrity Carbon Credits

Scientific consensus from the Intergovernmental Panel on Climate Change (IPCC) has acknowledged that to achieve the international goal of maintaining less than 2 °C warming, current greenhouse gas (GHG) emissions must be reduced and removed

Chad C. Papa and Melissa Kreye contributed equally to this work.

across all sectors (IPCC 2023). Protecting, restoring, and managing forests has long been acknowledged as a viable strategy for reducing and removing emissions, as forests already store and sequester substantial amounts of terrestrial carbon and play a pivotal role in regulating the Earth's hydrologic and energy cycles (Bonan 2008; FAO 2025; Fargione et al. 2018; Pan et al. 2024). Evidence has shown that managing forests and other ecosystems could provide 100 to 1000 Gt CO₂ equivalent (CO₂e) climate mitigation potential by the end of the century (Nolan et al. 2021).

Carbon markets are a growing market-based solution for addressing climate change, with over 9.3 million acres of US forests participating (Reis and Evans 2025). Since 2005, the total value of carbon credits sold in the global voluntary market has exceeded \$11.3 billion, with the majority of demand coming from nature-based emission-removal projects (Forest Trends' Ecosystem Marketplace 2025). However, in 2024 the volume of credits traded dropped by 25% and the average price of carbon dropped 5.5% (Forest Trends' Ecosystem Marketplace 2025). Declines in credit value have been partially attributed to concerns about over-crediting of carbon projects, with forest projects facing similar scrutiny (West et al. 2020; Badgley et al. 2022). Other analyses assert that existing protocols remain inadequate to ensure the long-term integrity of forest carbon credits (Sanders-DeMott et al. 2025), leading to a credibility issue and changes in demand (Balmford et al. 2023). The lack of alignment with the objectives of international frameworks such as the Paris Agreement and Nationally Determined Contributions may also undermine the credibility of the credits generated in the US, increasing the risk of double-counting carbon credits (Kreibich and Hermwille 2021).

Changes in demand for carbon credits are projected to recover over the next few decades. One report found 42% of Fortune Global 500 companies plan to use some type of carbon offset to meet their emissions reduction goals in the next 30 years (Climate Impact Partners 2024). While there are some concerns that carbon offsets may distract from other decarbonization strategies, recent research found that carbon credit purchasing is unlikely to crowd out internal decarbonization measures for most companies (Stolz & Probst 2025). However, within certain sectors, such as airlines, corporations will continue to rely on offsets to meet targets (Stolz & Probst 2025). Safeguarding the integrity of forest carbon credits used for offsetting, while also formulating net-zero solutions, will be critical to ensure real climate benefits today and into the future.

High-integrity credits represent a new phase of carbon offsets in which credits are graded and verified using requirements that promise long-term, real, durable, verified, and additional carbon storage. Recently, the Integrity Council for the Voluntary Carbon Market (ICVCM) identified ten core carbon principles (CCP) to categorize carbon projects as high-integrity. These ten core principles were designed to reduce confusion, overcome market fragmentation, and give buyers confidence that they are funding projects that make a genuine impact on emission reductions and removals (ICVCM 2025). The ICVCM has approved the first forestry protocols as high-integrity, including three Improved Forest Management (IFM), three afforestation and reforestation methodologies, and three biochar methodologies; however, as of mid-2025, only a small amount of credits have been pre-sold by a few carbon project developers under these methods (ICVCM 2025).

This paper summarizes key findings, challenges, and opportunities for research and education to support the development of high-integrity carbon credits, arising from a series of discussions with academics, practitioners, and experts in the spring of 2025. Further insights from the authors are also presented to better align research priorities with the development of high-integrity carbon credits. The discussions focused on six topics, including additionality, permanence, leakage, measuring, monitoring, reporting, and verification (MMRV), markets and the forest bioeconomy, and the social and ecological impacts of carbon markets and forest carbon credits. Our approach closely aligns with the Integrity Council for the Voluntary Carbon Market (ICVCM) principles, addressing the core technical, social, and governance issues required for high-integrity carbon markets. It is also conceptualized in Fig. 1, which illustrates how industry standards for nature-based carbon projects are embedded within broader markets and social and ecological spheres. Included

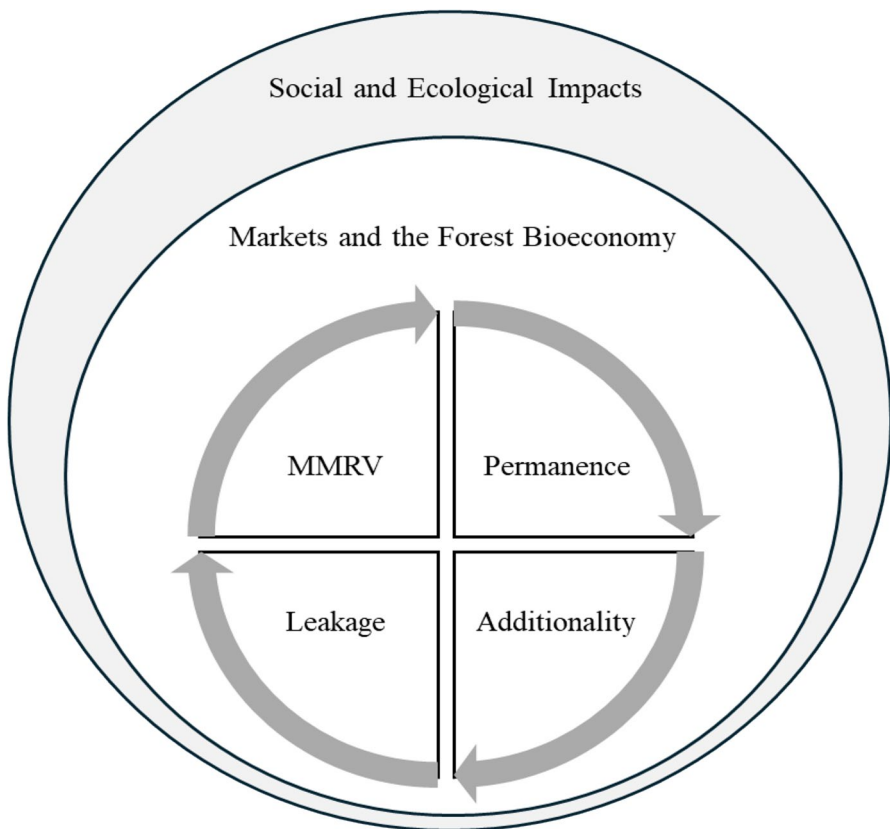


Fig. 1 A conceptual model illustrating how industry standards (i.e., additionality, permanence, leakage and measuring, monitoring, reporting and verification (MMRV)) for nature-based carbon projects are embedded within broader markets and social/ecological spheres. These areas serve as the foundation for increasing the quality and integrity of carbon crediting schemes, and thus play a critical role in supporting climate mitigation goals and advancing the well-being of forest dependent communities

are considerations for landowner decision-making, buyer motivations, and potential policy implications. The chosen topics were identified through expert insights, academic literature, and for their alignment with ICVCM core carbon principles and the ICVCM assessment framework both of which draw from available science and expert feedback. The six topics chosen are not exhaustive or representative of every facet of the voluntary carbon markets. However, they do cover important criteria to evaluate and identify challenges and opportunities for future research priorities to support the quality and integrity of carbon credits. Substantial linkages and overlap occur across each topic, but we found it beneficial to frame them as such to support dialogues between researchers, practitioners, and decision-makers.

Discussion panelists were selected for each session based on their subject matter knowledge (e.g., ecology, economics, policy, management) and their ability to speak to emerging debates using the Forest+Climate Learning Exchange Series (LES), an ongoing webinar series since 2017 that seeks to foster a more nuanced understanding about the relationships between forests, people, and the climate, as the venue to host the discussions (See Appendix A for list of panelists by topic). The panelists represented a wide range of institutions, including major research universities, non-profit environmental organizations, and private industry. Subject matter experts were either selected because of their knowledge of the field and previous publishing record, identified through peer-networks (e.g., perceived scientific contributions from peers), or for their professional experience in practical applications. This allowed the discussions to extend beyond academic theory, incorporating the perspectives of practitioners, advocates, and land management professionals. The involvement of private-sector representatives brought practical considerations about implementation and market function into the conversation. Audience participation also played a central role in shaping the discussions with an average of 96 active public participants per webinar. Public participation was advertised through professional list-servs, newsletters, extension networks, social media, and professional society memberships. Discussions also included moderated question-and-answer periods where public attendees were invited to share their own experiences, pose questions, and raise challenges from their work. These contributions broadened the dialogue to include forest landowners, extension professionals, policymakers, and community members, ensuring that the discussion encompassed not only expert viewpoints but also the lived experiences and concerns of those directly impacted by carbon market developments.

To summarize discussions, we employed two note takers in addition to the use of a third Artificial Intelligence (AI) notetaker. Each discussion was recorded and transcribed. We used a content analysis approach to identify and code themes and groupings of themes into broader categories. We employed a deductive approach drawing from our conceptual model to guide the creation of our research priorities and insights. Specifically, we (1) evaluate and summarize current discussions across the literature as they relate to the integrity of carbon credits; (2) identify current research priorities to support the quality and integrity of carbon credits; and (3) offer a summary of research, policy, and management implications to improve the accuracy and transparency and help overcome barriers to improve the functioning of voluntary carbon markets.

Summary and Findings from the LES Discussions

Additionality

To ensure additionality is real, the management practices or actions that occur must be different from “business-as-usual” practices either in timing, intensity, or type of activity. Emission reductions achieved voluntarily in the past, outside a forest carbon project, cannot be counted toward future carbon credits. Only when a property is enrolled in a project can the additional benefit be assessed by measuring carbon gains and losses at set intervals and estimating the carbon difference between the baseline (“business-as-usual”) and the new management scenario (Richards & Huebner 2012). Previously, developers used regional averages in tree growth, harvesting, and biomass production to set baselines. Regions with a high standard deviation around estimated averages are more likely to have projects or parcels that fall significantly above or below the mean, which can result in the over or underestimation of carbon stocks on those properties over time (Badgley et al. 2021). While this miscalculation in emissions reductions may wash out in the “law of averages”, it can make participation by landowners inequitable in regard to fair compensation. However, estimation of baseline emissions requires an understanding of localized disturbance regimes and the likelihood of frequency changes, creating inherent uncertainties and the risk of reversals (Teo et al. 2023; Anderegg et al. 2025a).

While standardization of estimating baselines and in turn additionality has benefits, the need for place- and project-based information to be incorporated into baseline estimations requires some level of flexibility and nuance (Haya et al. 2023) which has already occurred with recent shifts toward dynamic baselines (Bento et al. 2016). In the US, most baselines are being set using national forest inventory (NFI) data such as the U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis database (FIA) (Russell et al. 2025; Johnson et al. 2025), other inventory datasets, or satellite remote-sensing models. While this information is invaluable, significant uncertainties and gaps in the data exist, especially in areas with high carbon densities and ecological heterogeneity (Randazzo et al. 2023; Badgley et al. 2022). For example, many baselines in the western United States might not accurately capture carbon storage in drier forest systems over time. Legacies of fire suppression have created overstocked forests, so comparing carbon projects to these stands might not give us a good representation of carbon storage balance with other forest health and resiliency goals. Furthermore, baselines generally lack information on historical disturbance regimes which strongly influence current and future carbon stocks.

Disentangling the nuance between credits sold for emission reductions versus emission removals versus emission avoidance adds another level or complexity in determining the direct mitigation contribution of an individual credit. Emission reductions refer to activities that reduce GHG emissions that would have happened otherwise by changing management actions such as reducing high intensity harvesting, avoiding soil disturbances during harvesting, or reducing forest

degradation. Whereas removals refer to activities that actively remove atmospheric CO₂ by increasing net carbon storage over time. Finally, avoided emissions refers to the hypothetical prevention of emissions such as preventing deforestation or land-use conversion. All three, while grounded in science, have varying degrees of uncertainty to their climate mitigation efficacy (Buma et al. 2024).

Priority Areas for Improvement to Ensure Additionality

Gaps in consistency surrounding baseline establishment and utilization of national datasets are two challenges to ensuring additionality. More specifically, research to support carbon additionality could prioritize:

- The development of more consistent baseline measurement systems that explicitly include natural disturbance regimes such as fire, wind, insect and disease outbreaks, and drought-related mortality, consider future climate change impacts, and include mechanistic climate feedbacks, when necessary. The consistent and repeatable mapping and modeling of forest carbon quantities and distribution as well as the frequency, severity, and timing of disturbances, and the underlying mechanisms driving change could provide improvements to baseline measurements (Dye et al. 2024). Furthermore, integrating predictive models that no longer rely on historic trends as analogs for the future as changes are more likely to be pronounced and could reduce additionality estimations (Seidl et al. 2017).
- Improving quantitative evidence of management impacts on carbon storage and sequestration through empirical research, including understanding the long-term ecological effects on delaying harvest on forest growth, structure, and function, and their relationship to carbon storage and permanence as significant uncertainties remain on forest characteristics (Galik and Jackson 2009; Healey et al. 2025; Zeng et al. 2026). Remote sensing platforms and other data-driven methodologies provide certain strengths to evaluate the effectiveness of carbon projects through timely data collection and improved spatial resolution (Coffield et al. 2022; Dye et al. 2024; Teo et al. 2023). The development of spatially explicit maps for forest characteristics, carbon storage, and project activities blended with allometric equations (Quegan et al. 2019; Altman et al. 2024) could enable better near-real time monitoring (Novick et al. 2022).
- Continuing support, development, and leveraging of NFIs, other publicly available inventory data, remotely-sensed technologies, and machine learning tools to more accurately assess optimal carbon stocks using geographic and forest-specific information. Integrating recent advances in data-driven tools, improving model-data integration, and establishing nationally consistent frameworks can further enhance forecasting capabilities to support baseline and additionality estimation (Munro et al. 2025) especially when quantified at varying spatial scales.
- The ongoing development of flexible modeling approaches and workflows that allow for the continual incorporation and improvements as new data, both inventory and remotely-sensed datasets, come online to improve baseline estimation throughout the project life cycle with explicit protocol guidance that allows for

incorporating innovative methods as they arise. For example, recent advancements in synthetic control methods, statistical analysis, matching, and machine learning, paired with dynamic ex-post counterfactual methods show promise in correcting flawed ex-ante projections (Yu et al. 2026). Substantial opportunities also exist to leverage pre-existing data to provide more transparent, reproducible, and objective validation of additionality claims but require further operationalizing of data fusion approaches (Novick et al. 2022).

A broader framework to estimate and monitor additionality that integrates consistent baseline measurements with spatially explicit mapping fused with ground-based measurements can provide substantial improvements to current additionality measurements. Further integrating climate-driven mechanistic feedbacks for disturbances and climate impacts from process-based methodologies potentially provides stronger predictive power (Novick et al. 2022; Dye et al. 2024; Munro et al. 2025). For example, drawing from methods employed in earth system models and other terrestrial biosphere models (Fisher et al. 2018), while not broadly tested yet (Novick et al. 2022), could reduce uncertainty in predicting carbon dynamics for carbon projects. Advances in remote-sensing platforms, including space-born platforms and machine-learning driven approaches, may also offer substantial gains in the accuracy and precision of additionality estimation, especially when coupled with rigorous and nationally consistent forest inventory data developed under rigorous nationwide frameworks, which has yet to be done. This requires advancements in data fusion techniques, ideally available as open-source user-friendly platforms, to test counterfactual estimation.

Permanence

The concept of permanence holds that the additional emissions reductions should not be temporary but provide lasting benefits, akin to avoiding the use of fossil fuels in the first place. In forest ecosystems, the pursuit of permanence often involves managing non-atmospheric carbon stocks (e.g., biomass) so that storage remains relatively stable or increases on the landscape over the project's duration (Honegger et al. 2021). To date, the economic viability of forests is largely dependent on timber harvesting. Compensation for delays in harvest to store more carbon would have to recover revenues forgone in order for forests to remain economically viable. While this may be achievable on industrial forest lands, which are often managed with perpetuity in mind, it presents a unique challenge on nonindustrial forest lands where land tenure and planning timelines are much shorter.

Longer and larger projects are generally exposed to more risk and frequent reversals which in turn determines the size of the buffer pool (Galik et al. 2016). It has been shown that the size of these pools is generally too small to cover the liabilities associated with a widespread catastrophic loss of forests (Badgley et al. 2022; Anderegga et al. 2025a, 2025b; Wu et al. 2026). The California Air Resources Board buffer pool has already experienced a significant decline in active credits due to wildfire, and this is expected to increase as risk of wildfire hazard in the western US remains

high into the foreseeable future and leads to a buffer pool that is approximately 6-times too small currently (Carbon Plan 2024; Francis et al. 2023; Wu et al. 2026). Projects that have multiple smaller parcels distributed throughout a region could be less susceptible to large loss events. However, smaller parcels may also be at risk of inconsistent management due to distances between parcels, economies of scale, and frequent changes in private forestland ownership.

For projects to achieve permanence, and be economically viable, management strategies and buffer pool size must be balanced with expected risk and based on rigorous data (Wu et al. 2026). Future climate conditions may also bring more complexity and can even serve as a multiplier of risk because a warmer and drier climate can increase the probability of individual disturbances and multiple simultaneous disturbances, in addition to driving potential decreases in the rate of primary production and recovery (Hurteau et al. 2025). The potential for increasing rates of disturbance means that ecosystem responses to historical disturbance regimes may no longer serve as a reliable analogue into the future (Seidl et al. 2017).

The current differences in monitoring periods and buffer pool requirements create inherent discrepancies in the value of each credit generated and is partially dependent upon the specific protocol and methodology employed (Galik et al. 2022). Establishing a standardized time for monitoring, which could signal how long a credit is valid for, could help strengthen claims of permanence as there is wide variance in the different approaches and tools utilized by protocols to assess risk (Sanders-DeMott et al. 2025). Estimates of effective buffer pool size also depend on the timing of emissions reductions, to limit peak temperatures in the atmosphere. Peak warming is expected in the 2070s-2090s, with more pessimistic projections pushing that date off until 2150 (Lenton et al. 2023). Peak warming is based on the idea that some surfaces (e.g., oceans) release heat and/or CO₂ slowly back to the atmosphere, contributing to a gradual increase in temperatures even if emissions slow down. This means prioritizing emissions reductions in the short term (e.g., sale of cheap low-integrity carbon credits that are expected to provide emission reductions for 20–30 years), may fall short in addressing broader climate impacts (Matthews et al. 2022). Instead, long-term investment in ecosystem health and resilience to stabilize carbon stocks, along with durable additional carbon storage (Dye et al. 2024), may be a more appropriate strategy for adapting and mitigating climate change through periods of peak warming.

Priority Areas to Address Permanence Challenges

Threats to permanence for projects can be addressed in a multitude of ways. Improved data sources and clear guidance can lead to improved measurement and monitoring of carbon pools. Specific areas of research related to improving permanence include:

- The development of more rigorous, consistent, and transparent risk assessments that leverage inventory data, advanced mapping techniques, and AI technologies (e.g. Wu et al. 2026). Similar to additionality monitoring, fusing data streams and methodologies, with particular attention to developing spatially explicit

maps, can leverage next-generation platforms that allow for wider spatial extrapolation (Novick et al. 2024a), moving towards wall-to-wall risk mapping that integrates estimation of carbon storage (Wu et al. 2026), vulnerability and risk assessments, and other forest characteristics.

- Incorporating geographic and place-based information in a standardized way about threats and climate-induced challenges facing specific forests (Lecina-Diaz et al. 2021) such as spatially explicit wildfire risk assessments and insurance mechanisms. The use of vulnerability assessments paired with climate change predictions can better align project activities with the intersection of broader management goals (Roshani et al. 2022). When possible, incorporate climate change projections when assessing the risk of reversals through more mechanistic feedbacks to reduce forecasting uncertainty (Novick et al. 2022).
- Identification of appropriate thresholds for carbon storage by pool over a standardized period of time while considering the residence time, durability, and stability of specific forest carbon pools being measured that seeks to not conflate stocks versus fluxes, a persistent challenge in quantifying credits (Korner 2026).
- Establishing better criteria for what a carbon credit represents that does not conflate carbon emission types, ideally leveraging nationally or internationally recognized datasets. Recent debates that seek to rectify the temporary nature of biogenic carbon storage and better resolve the time value of carbon storage (Parisa et al. 2022; Matthews et al. 2023) across emission types could provide insights into trade-offs between biogenic carbon storage, fossil-fuel consumptions, and other forest benefits such as biodiversity.
- Identification of pathways for different industries to co-generate carbon credits by leveraging different mitigation strategies (e.g., combine engineered and nature-based solutions that include wood products) (Hanssen et al. 2020; Lehmann et al. 2021; Runkle 2022). Additionally, identifying policy opportunities for forest-based supply chain insetting, a strategy to reduce or remove GHG emissions directly within the value chain, paired with wood substitution can contribute to increased resiliency across the value chain (Ludvig et al. 2024). For example, pairing silvicultural techniques such as salvage harvesting for bioenergy creation have shown synergies between supply chain sustainability and climate mitigation potential (Mansuy et al. 2018)
- Informing the design of flexible standards and protocols that allow for buffer pool contributions to vary depending on project-specific risk assessments but are applied consistently across programs. Developing improved metrics to address future operational challenges such as contract lengths, the transfer or sale of properties, and forest management activities could reduce internal project risks. Furthermore, operationalizing socio-economic indicator monitoring designed to increase equitable participation could serve to improve future monitoring and decision-making, supporting project success (Chan et al. 2012; Kowler et al. 2020).
- Improve understanding of how silviculture and other adaptive management approaches affect carbon permanence especially as it relates to forest ecosystem vulnerability and risk including the exposure, sensitivity, and adaptive capacity of forests under a changing climate. Increasingly there are efforts to better

quantify the role of specific management techniques such as cuttings, thinnings, prescribed fire, and other climate adaptive treatments have on forest diversity, complexity, and other structural and functional outcomes in addition to climate change mitigation and adaptation (D'Amato et al. 2011; Palik et al. 2020; Nagel et al. 2026). However, explicitly relating these relationships between forest ecosystem characteristics back to management prescriptions and carbon permanence would better inform how forests respond, cope, or adapt to climate change stressors potentially improving understanding and quantification of carbon permanence under a changing climate.

Due to complexities in determining forest carbon permanence, future research could prioritize identifying, defining, and assessing risks across three primary categories including internal risks such as project management, financial viability, and opportunity costs, external risks including land tenure and stakeholder participation, and natural risks from disturbances and other climate-driven stressors (Dhond et al. 2026; Wu et al. 2026). Integrating multiple data streams, mapping, and machine learning techniques can improve assessing natural risk at increased spatial and temporal scales. Pairing recent advancements in monitoring permanence with improved thresholds and definitions for determining the durability and stability of individual carbon pools within the ecosystem could further support credibility claims (Dye et al. 2024). Identifying opportunities where nature-based projects can be paired with engineered solutions could provide additional credibility to permanence for example, pairing forest management activities that reduce risk to wildfire through thinnings or other fuel management activities with engineered forms of carbon capture such as bioenergy with carbon capture and storage, biochar, or other engineered forms of carbon storage (Birdsey et al. 2018; Xie et al. 2023).

Leakage

Leakage is assumed to vary both geographically and temporally, as it can span jurisdictional boundaries, timber markets, and timescales, modifying the circumstances both inside and outside the intervention area. Factors driving variation in understood leakage include the offsetting protocols, spatial extent, temporal scale, size of the intervention area, forest characteristics, type of management treatments, history of previous management, and local policies (Kallio and Solberg 2018, Sohngen and Brown 2004, Gan and McCarl 2007, Sun and Sohngen 2009). Understanding the intensity of forest management within the project intervention area can help determine the potential risk of leakage. For example, deferring harvest in areas where intensive forest management is more common can lead to greater leakage due to others switching their harvesting activity in response to short-term changes in market prices. More specifically, research shows that market leakage will be lower if demand for timber is elastic with respect to price or alternative products are not substitutable, and higher when supply is relatively more elastic with respect to price, substitutable goods that have a higher net carbon footprint, or supply (Filewod and McCarney 2023).

Market behavior in 2024–2026 shows that stumpage prices in the eastern US have *not* been responding strongly to changes in lumber or housing demand, and in many regions, prices are flat or even declining, despite shifts in downstream markets (e.g., Lamichhane et al. 2025; Li 2026). If timber prices do improve, and/or carbon prices become more competitive with timber harvesting, then harvesting pressure may shift to landowners currently barred from carbon projects due to small property size or lack of proof of ownership (e.g., heirs' properties), which may have implications for the use of sustainable harvesting practices.

While all standards require considerations for leakage which is assumed to be greatest in areas with more intensive timber management, some project designs may create the possibility of positive spillovers, such as incentivizing tree planting or other carbon-positive behaviors not directly attributable to the carbon project (Daigneault et al. 2025). Establishing a set of criteria or pre-conditions such as geographical extents, species or forest type, local governance, or local timber markets could potentially aid in assessing and mitigating the risk of leakage as leakage is inherently a market-mediated phenomenon. These pre-conditions could also help to quantify more appropriate time horizons in determining project permanence, additionality, and feasibility. Furthermore, differentiating between shifts in non-market motivated harvesting behavior, for the purposes of stand health (Richards and Andersson 2001) and market-mediated shifts for revenue-seeking purposes (Van Kooten and Johnston 2016) remains challenging, as any shifts in timber harvest can cause subsequent fluctuations in timber pricing. A more holistic understanding of leakage will also require measuring the full carbon life cycle of wood products and their substitutes.

Priority Areas to Address the Risk of Leakage

Addressing the concerns about leakage in forest carbon projects requires investment in technology and research that can increase the capacity to model and monitor the impacts of leakage on crediting in forest carbon projects. Specific research priorities include:

- Investigation of the potential for AI technologies, drones, and novel modeling approaches to reveal predictive patterns and better account for potential leakage at regional to global scales (Daigneault et al. 2025). This could also help support strategies that account for leakage over longer periods of time and inform leakage causality in a spatially explicit manner, an area of growing emphasis (Rana et al. 2026).
- Improving understanding of current stand density and management regimes and history of neighboring forests to select supply chain alternatives from either reducing harvesting or extending rotation lengths within the project area. For example, identifying areas of overstocked lands to replace potential delays in harvest elsewhere (i.e., *how do we use overstocked lands and timber stand improvement treatments to mitigate the impacts of timber harvest from delayed harvest rotation to maximize benefits across the landscape?*).

- Identification and quantification of sources of leakage variation and the causal drivers across forest types and regions to better understand how leakage rates may differ across space and time (Pan et al. 2020; Rana et al. 2026). Determining if leakage rates should vary based on project location and forest characteristics to improve estimation could also help improve estimation of additionality and permanence. Further, improving the conceptual and practical distinction between timber leakage and carbon leakage could improve overall monitoring and estimation of leakage (Daigneault et al. 2025).
- Informing the development of integrated land-use policies to prevent leakage ‘leap-frogging’ across jurisdictional boundaries, a practice more common in urban sprawl and growth management. Integrating the use of spatial tools into land-use policies to better understand the context specific spatial trends of leakage could lead to more holistic policies that seek to limit potential negative downstream effects outside the normal bounds of monitoring and potential spillover to other jurisdictional boundaries.
- Develop tools to better measure carbon leakage rather than harvest or forest area leakage across the range methodologies now applied to assess leakage in the literature. Embedded in this is a better understanding of the temporal dimensions of any carbon leakage estimate, including assessment of whether discounting should be applied.

Together these actions would strengthen the credibility of estimating, tracking, and reporting leakage that arise from direct project activities and from non-target behavior shifts in response to changes to economic incentives. Pairing innovations in carbon accounting across scales with land-use policies can help developers, auditors, and registry specialists identify areas of synergy between current stocking levels of forests as compared to historic stocking. Doing so has the potential to prioritize areas where forest characteristics make sense for elongating rotation lengths along with pairing those actions with areas where reducing stocking provides additional ecological benefits, which can alleviate perturbations to forest supply chains. Lastly, improving the spatial and temporal scales at which leakage is tracked can help determine better leakage rates based on project location, forest characteristics, and potentially prevent the ‘leap-frogging’ across jurisdictional boundaries.

Measuring, Monitoring, Reporting, and Verification (MMRV)

A key inflection point when conducting MMRV is deciding which model or approach to use to measure carbon (Premier et al. 2025, Anderson-Teixeria and Belair 2021, Bagstad et al. 2013, Novick et al. 2022, Cook-Patton et al. 2021). Unless every tree in a forest is cut, dried, and weighed, tree carbon measurements are all based on estimates and vary from model to model. Different approaches provide varying benefits and drawbacks, therefore creating uncertainty in reporting data (Daigneault et al. 2022). Many allometric equations have not been updated in decades and aim to reflect merchantable timber alone, oftentimes under counting estimation of carbon estimation in the branches, tops, and roots of trees (Doraisami

et al. 2024, Lim et al. 2024, Restrepo et al. 2025) and frequently do not account for rates of decay. Moreover, changes in carbon stored in forest soils are often omitted from the calculus. Remote sensing technologies provide immense potential to estimate changes in the volume of living biomass at larger scales; however, the margin of error varies significantly across different platforms (Tian et al. 2023, Knott et al. 2023, Borsah et al. 2023), and all methods still require on-the-ground calibration and verification (Xu et al. 2025).

The emergence of improved direct ecosystem-scale monitoring of carbon fluxes using technologies such as eddy covariance flux towers and earth systems models have increased the accuracy of baselines (Novick et al. 2022) as inventory data can miss stocks or stock changes concealed by landscape heterogeneity and generally do not provide information on non-CO₂ GHG fluxes. Recent evidence using ecosystem-scale observations suggests that carbon uptake might be significantly greater than estimates reported using stock-change based approaches (Novick et al. 2024b); however, more research is needed to more fully understand the use of such models within policy frameworks and users (Woodall et al. 2025).

The costs associated with the MMRV of carbon remains one of the most significant barriers to project development and maintenance. Project auditing adds another layer of cost and time to any given project, especially considering the limited number of certified professionals (Vaughan et al. 2022; Eastman et al. 2025). Simplifying these processes could allow more buyers to enter the market, as increased transparency and reduced costs could alleviate potential risks within the marketplace. Recent advancements in both the temporal and spatial resolution of remotely-sensed datasets such as satellite imagery, airborne and spaceborne LiDAR platforms, drone imagery, and other terrestrial laser scanners offer immense opportunity to decrease labor costs; however, measurements still largely must be ground-truthed and calibrated to forest inventory plots to ensure veracity. Streamlining data across platforms with the use of machine learning or other data-driven approaches have shown encouraging results to improve both the cost-efficacy and accuracy of estimation. In addition to technical accuracy, the diligence of professionals involved in information management is also crucial.

Priority Areas to Improve the Measurement, Monitoring, Verification, and Reporting of Carbon

Challenges surrounding MMRV can lead to reduced integrity of forest carbon credits. Improving methods can help bolster MMRV. Further research and knowledge could help to increase the efficacy of systems in place. Research priorities include:

- Advancing the use of innovative data-driven tools and technology such as satellite imagery, LiDAR, drone imagery, or machine learning to decrease costs while simultaneously increasing accuracy in the development of MMRV systems. Leveraging accounting methods from local to regional scales by blending direct assessments of carbon fluxes (i.e., flux towers data) into inventorying, biometric, and other remote sensing observations can help reconcile different spatial and temporal scales (Novick et al. 2022).

- Improve understanding and estimation of lateral losses of carbon through empirical studies (i.e., losses of soil carbon to water runoff). Answering fundamental carbon accounting and transfer questions can help improve the precision and accuracy of project-scale monitoring and verification further supporting more reliable baseline, additionality, and leakage estimation.
- Inform the integration of operational considerations into the development of MMRV systems to improve scalability to create systems that are consistent and therefore more repeatable and cost-effective while ensuring accuracy including the development of more standardized reporting criteria across methodologies for wood products (Arodudu et al. 2023).

The rapid development and deployment of MMRV systems that address current technological, data, and transparency issues will support increased trust and accessibility. Further, fundamental questions about the ultimate fate of carbon within terrestrial ecosystems such as the lateral loss of carbon and the potential lack of measuring all carbon fluxes still need to be answered (Novick et al. 2024c). Blending inventory-based approaches with multi-scalar based approaches such as flux towers, earth system models, terrestrial biosphere models, and other recent advances in machine learning offer plausible pathways forward but require cross-sector and cross-disciplinary collaboration. However, technological advances should consider operational impacts in monitoring project-scale carbon emissions, understanding fundamental trade-offs between costs, useability, and accuracy.

Markets & The Forest Bioeconomy

Voluntary carbon markets are inherently complex because they involve diverse actors across the forest production chain, operating simultaneously at local and global scales. Management decisions made by forestland owners in particular play a significant role in determining the future of forest carbon projects. Perceived opportunity costs across management priorities are likely to affect landowner participation in projects (Soto et al. 2016). A recent meta-analysis of studies assessing acceptable payment levels revealed that production-oriented landowners require nearly three times as much compensation compared to owners who engage in more passive forest management, due to perceived opportunity costs (Sharma and Kreye 2022). Ongoing uncertainties surrounding the compatibility of easements, preferential tax treatment, and enrollment in harvest deferral programs create additional challenges to enrollment (Diedrich and Clay 2025). However, the current low stumpage prices could incentivize landowners to prioritize carbon revenues as a primary source of income (Busby and Binkley 2021; Lamichhane et al. 2025). Strategies that encourage the market entry of early adopters are still needed to establish proof of concept until market prices improve as significant uncertainties remain with contract lengths and social compatibility (Khanal et al. 2017; Kerchner & Keeton 2015) an issue that has only increased in importance given the pace of change in forest carbon markets (Sharma and Kreye 2022). Current avenues being explored include diversifying contract styles by subsidizing high startup costs or offering large upfront incentives.

Widespread adoption of forest carbon projects could have both direct and indirect ripple effects throughout the forestry supply chain, job market, and harvesting infrastructure. Long-term trends show declines in harvesting, closure of regional mills, and volatility in timber prices (He et al. 2021; Eastman et al. 2025) which all have critical implications for a robust timber economy and assumptions that underpin the standard of additionality. Areas such as New England have already seen fewer landowners harvest timber because of social challenges and decreasing parcel sizes (Levesque 2024). This decrease has led to subsequent declines in the forester and logging job force and further effects the financial viability of mills. Increased adoption of carbon markets could exacerbate challenges for struggling wood markets and potentially incentivize unsustainable harvesting practices or no harvesting in response impacting rural economies from local to regional scales (Bubser et al. 2023; Cameron et al. 2024). If the challenges facing the timber industry are more structural than competitive (He et al. 2021), expanding access to investments for emission reductions within the wood products sector may be one way of supporting a reliable supply of renewable wood and fiber.

Future buyer involvement in carbon markets is also uncertain. There is still a lack of clarity regarding how credits will be utilized to meet zero-emission goals, enhance ESG ratings (environmental, social, and governance), and for other ethical or corporate social responsibility reasons (Agbakwuru et al. 2024). In the European Union, carbon disclosure laws have been established, incentivizing companies to reduce their carbon footprint (Breshani 2025). While this does not directly impact US-based companies, any companies that do business in Europe must comply. Additionally, the type of assurances required by investors, corporations, or other buyers to manage risk when trading credits remains poorly understood (Trouwloon et al. 2023).

Priority Areas to Foster a More Sustainable Bioeconomy

A more sustainable bioeconomy requires an advanced understanding of key interactions between ecological systems, new and existing markets and regulations. Research priorities include:

- Advancing bioeconomic modeling analyses for ecosystem service provisioning under future pathways to help inform tailored strategies that balance competing objectives (i.e., carbon, timber, wildlife) on non-industrial forest lands (Carovillano 2025)
- Quantifying the return on investment financing for nature-based carbon projects that focus on building resilience within ecosystem systems, as compared to timber production (Elias et al. 2025), and clarifying fundamental trade-offs between goals.
- Identification of incentives packages for landowners that balance multiple management objectives and high up-front costs with future returns, which can increase the long-term sustainability of projects (Gazal et al. 2025) as well as increasing guidance on the tax treatment of carbon income and tax compatibility of projects with other tax preferential treatments (Diedrich and Clay 2025).

- Informing and identifying financial schemes for leveraging low-value woody biomass production (e.g., biochar, mass timber) as a strategic resource for achieving comprehensive forest restoration goals and provision of renewable resources (Ghosh et al. 2025). Including the assessment strategies for tracking climate benefits, recovering waste, and retaining values within wood products supply chains (Farjana and Ashraf 2025).
- Improvements in assessing how regulatory restrictions for compliance markets can influence the voluntary market including understanding what drives the price of a carbon credit, drivers of supply and demand, and support for methodological improvements.
- Investigation into the type of credits that buyers need or are looking for to provide increased transparency especially as investments prefer low-risk active restoration-based projects rather than other more passive approaches (Lofqvist et al. 2023).
- Assessment of the trade-offs for local and regional economies between wider voluntary carbon market adoptions and wood markets including implications for the forestry and logging workforce, logging infrastructure, mill financial viability, and incentives of unsustainable harvesting practices.

A more sustainable bioeconomy depends on a deeper understanding of how ecological systems, markets, and regulatory frameworks interact over time, particularly in forested landscapes dominated by non-industrial private ownership. Research priorities emphasize the need for integrated bioeconomic modeling to evaluate how different future management pathways affect ecosystem services such as carbon storage, timber production, and wildlife habitat, and to help identify strategies that balance these often competing objectives. Related work highlights the importance of comparing the financial performance of resilience-focused forest carbon projects with traditional timber production, as well as designing incentive packages that help landowners overcome high upfront costs while still realizing long-term economic returns. Together, these efforts aim to improve participation, equity, and durability in forest-based climate strategies.

Another major focus is understanding how financial and market mechanisms can support restoration and value creation without undermining ecological goals. This includes developing financial schemes that leverage low-value woody biomass—such as biochar or mass timber—as strategic resources to advance forest restoration, provide renewable materials, and retain value within regional economies. Research also points to the need for better methods to track climate benefits, recover waste, and maintain value across wood-product supply chains. At the same time, clearer insight into how regulatory requirements in compliance markets influence voluntary carbon markets—especially through price formation, supply-and-demand dynamics, and methodological rules—is essential for improving transparency and credibility.

Finally, the literature underscores that economic and social impacts must be explicitly considered as forest carbon markets scale. Buyer preferences increasingly favor transparent, low-risk credits tied to active restoration rather than passive management, which has implications for how credits are designed and valued. Widespread adoption of voluntary carbon markets may also create trade-offs for local

and regional economies, including effects on forestry employment, logging infrastructure, mill viability, and the risk of unintended harvesting or management cessation. Addressing these challenges requires standards and protocols that account for potential perverse incentives, alongside improved tracking and quantification across the forest-product value chain to better evaluate both climate benefits and economic consequences.

Social and Ecological Implications

The benefits provided by forest carbon projects have largely been directed towards credit buyers and project developers oftentimes leaving behind the landowners and communities where projects occur (Sass et al. 2021). To date, the largest volume of credits sold in the California compliance market have gone to corporate lands with largely mixed results as to the effect on local communities (Pan et al. 2022) such as limited economic returns (e.g., tax revenue) as compared to other land-use options (Aggarwal 2020). Therefore, there is an opportunity to better incorporate local communities into project design to ensure the appropriate socio-ecological safeguards exist (Romm et al. 2025) and to foster outcomes which align with the needs and values of all individuals and communities (Eastman et al. 2025).

Aligning projects with local needs and generating community buy-in often requires early and iterative engagement to co-create projects with community leaders. Co-designed principles are particularly important when working with communities that have historically low levels of trust, including predominantly Black and Indigenous landowners (Caperon et al. 2022; Urquhart et al. 2023). Involving younger generations supports workforce development and continuity of projects since contracts often extend beyond the lifetime of the original landowner (Bhaduri et al. 2022). In order to foster meaningful engagement, project developers could consider processes that contain capacity building for local participation, address disparities in power across actors (Mathur et al. 2013), and acknowledge project implementation has innate social costs and land rights for rural communities (Pan et al. 2022).

Wider market adoption among landowners and stakeholders could have profound implications for local, municipal, and state revenues due to a shift in timber harvesting which could influence the forestry workforce and forest products sector. While forest carbon projects are widely seen to provide social and environmental benefits, weaker markets for timber or wood products could have more significant negative effects on rural natural resource dependent communities (Moioli et al. 2025). Furthermore, a slowdown in active timber management could have other effects on the future health and resilience of forests including: (1) shifts in risk from natural disturbances due to increased fuel and stocking, and (2) a lack of financial investments in planting and forest regeneration post-disturbance, potentially threatening to counteract climate gains from forest carbon projects.

Forest carbon projects present an opportunity to promote multiple ecological co-benefits which may align with the needs and values of local communities such as wildlife habitat protection, soil erosion control, biodiversity, and water quality (Deal

et al. 2012; Lin et al. 2013). Managing forest biomass also contributes to other ecosystem service benefits such as food safety, energy provision (i.e., woodfuel), genetic diversity, and cultural services (Millennium Ecosystem Assessment, 2005, Díaz et al. 2018, Caldwell et al., 2023). Particularly, biodiversity and using native species have become a priority in the design of many nature-based carbon projects. While the significance of biodiversity outcomes is widely recognized, fostering these projects and understanding their contribution to high-integrity credits will benefit from further research and methodological development (Pan et al. 2022).

Priority Areas to Ensure Socio-ecological Benefits

To support the generation of high integrity carbon credits, there is a growing need to recognize socio-ecological risks and responsibly engage communities in culturally appropriate manners. Research and education priorities include:

- Support the development of locally-informed safeguards and standards for engagement with vulnerable communities to ensure projects represent community values as evidence has shown that low-income regions face higher costs when forest projects fail (Moioli et al. 2025). There already is abundant literature about safeguards and co-benefits throughout the global South and tropics. However, less emphasis on applying principles (Vanclay, 2017) to gain project acceptability, legitimacy, and trust within the domestic US context exists.
- There is an opportunity to build upon the research on the socio-economic risks involved in project design and development (Pan et al. 2022). Topics may include operational challenges related to contract lengths, the transfer of properties, and implications for future forest management, all of which can impact the permanence of a project.
- Better defining the idea of commodifying biodiversity as a credit, in addition to carbon benefits, is a topic of increasing interest (Webb et al. 2025). One novel approach is to monitor for multiversity as estimated based on high-throughput molecular identification of soil meiofauna, fungi, bacteria, protists, plant roots, and other organisms shedding DNA into soil (Tederloo et al. 2024). However, estimating the efficacy and accuracy of such efforts still needs to be tested.
- How to best frame educational initiatives about climate change, and natural climate solutions to increase awareness of how and where projects are implemented, how community consent is informed, and how biodiversity is protected (Seddon et al. 2021). These conversations can also help foster more regenerative relationships between people and nature (Welden et al. 2021). Improve metrics and evaluation of trade-offs between carbon and other co-benefits to support protocol design by understanding that other ecosystem services from forests such biodiversity, climate adaptation, and human well-being can help support and enhance mitigation over longer timespans (Smith et al. 2022; Donatti et al. 2022).
- Support continuing education opportunities for forest professionals and technical service providers working in outreach and engagement with forest landowners to ensure uptake and integration of current issues, concerns, and community needs.

- Inform the design of protocols that encourage biologically and culturally appropriate projects that prioritize native species, ecological integrity, and the protection and restoration of wildlife habitat as recent evidence has arisen to the latter (Badgley et al. 2021; Maron et al. 2025).
- Specifically seek out Indigenous community and underserved landowner participation in project co-design to elevate culturally relevant practices and species, prevent harm, and ensure positive local outcomes.
- Investigate the social cost of AI and machine learning usage in academic research and forest carbon projects for environmental impacts on energy supplies, ecosystems, and hydrology (Olawade et al. 2024; de Roucy-Rochegonde and Buffard 2025).

Pursuing research priorities that elucidate human dimension challenges within standards and protocols, can help address socio-economic risks that hamper project permanence (Huettner, 2012). Preparing communities to be able to advocate for themselves to better align carbon project goals with needs will also support the long-term success of these projects. The literature is rife with examples where marginalized communities bear the brunt of poor governance, natural resource management, and financial incentives. Developing locally informed safeguards relevant to communities within the US can make a significant impact to not only prevent harm but move beyond the do-no-harm paradigm to generate equitable benefit sharing within and among communities (Cubas-Baez et al. 2025). Reframing the conversation about climate change, carbon offsets, and natural climate solutions, allowing stakeholders to engage with discourse relevant to their context would seek to build a stronger consensus shifting power from more top-down to bottom-up decision-making. Doing this requires improvements in metrics and evaluation techniques used to understand co-benefit sharing, climate impact, and their trade-offs to better support mitigation efforts. Lastly, protocols that encourage and incentivize biologically and culturally appropriate projects that actively integrate Indigenous communities and local knowledge to increase project participation allow for increased project legitimacy and transparency (Cadman 2013).

Summary and Future Research Priorities

Our discussions highlighted a number of emerging priorities to support the integrity of forest carbon projects. Moreover, they illustrate how project standards, forest land conditions, people, and markets are intertwined when generating forest carbon credits. Our discussions overwhelmingly emphasized the importance of transparency, information sharing, and broad communication, especially with local actors, forest users, and the public. We also identified gaps in communication between academics, businesses, project developers, policy makers, landowners, and the broader public. Additionally, an emphasis was placed on the need for community members to be involved throughout the process to ensure they can fulfill the robust management practices needed to ensure high-quality credits, avoid perverse economic incentives, and that protocols are culturally and ecologically appropriate.

Another important theme to highlight was the emphasis on harnessing the power and potential of new technologies and open data sharing to make the monitoring and prediction of forest carbon dynamics more efficient and accurate. The ability to use lower cost drones for new imaging, advanced data-driven modeling techniques, increasing the use of satellite remote-sensing, and the emergence of AI and other machine learning technologies could help to improve the integrity of credits. Advances in technology can help to enhance not only the accuracy of baseline estimation but also better predict and monitor leakage risk and improve estimations of reversal risks under future climate projections. These data and technologies are invaluable to creating more robust protocols and in turn improving the underlying science of carbon accounting while potentially reducing costs.

Overarching Research Priorities to Increase the Integrity in Forest Carbon Credits

Here we summarize overarching research priorities with implications for carbon science and methodologies, policy, and management. Future research and collaboration across these three focal areas would help to increase the integrity of forest carbon credits.

Carbon Science and Methodological Research Priorities

To support higher-integrity carbon credits, the work of scientists, academia, and other knowledge producers aims to advance the underlying science used to model, project, track, and determine the ultimate fate of carbon. This work could emphasize defining the role and evaluating trade-offs of recent technological advances, such as AI technologies and remotely-sensed data, in project development and monitoring to reduce costs, increase accuracy, and validate additionality and permanence focused on integrating and fusing data streams and emerging technologies. There is still a growing need to quantify the long-term ecological impacts of forest carbon projects on forest growth, structure, function, and adaptive capacity, and their relationship to carbon storage and sequestration which can be supported by the continuation and expansion of forest inventory-based efforts both in spatial and temporal intensity, such as NFIs. There is an opportunity to increase understanding of what constitutes a carbon credit as it relates to emission avoidance, reductions, and removals with an added emphasis on durability across carbon pools. To reduce uncertainty of forecasted predictions, methodologies may be improved to track and quantify leakage, baseline emissions, and project additionality that fuse data sources and mechanistically incorporate climate change predictions, climate feedbacks, and historical disturbance regimes into baseline estimations. Further, there are still gaps in the literature related to socio-economic risks involved in project design and development.

Policy Research Priorities

Panelists and participants discussed policy-relevant topics requiring further emphasis that could help support the health of carbon markets. These topics include: creation

of locally informed safeguards and standards for engagement with vulnerable communities to ensure projects represent community values and positive societal outcomes; increased consistency across project protocols and standards to increase the transparency and create alignment on estimating project risk, buffer pool estimation, and leakage quantifications; the establishment of requirements for transparent and open-access project reporting to avoid the risk of double counting, as well as transparency in carbon pricing; The design of projects that consider trade-offs between carbon and other forest co-benefits and ensure equitable benefit sharing across all actors.

Forest Management Research Priorities

Discussions related to on-the-ground implementation of forest carbon projects highlighted how the identification of biologically and ecologically appropriate actions that prioritize native species, wildlife, and other culturally appropriate practices that still provide climate mitigation benefits and the purposeful incorporation of Indigenous communities and underserved landowners to better co-design projects that employ culturally relevant practices can help strengthen the efficacy and equity of forest carbon projects. Furthermore, forest management research priorities provide an opportunity to highlight the need to improve understanding of how silvicultural practices and other forest management actions influence carbon stocks and fluxes over time and how management decisions interact across multiple priority areas including additionality, permanence, leakage, and the bioeconomy influencing the integrity of carbon credits. Particularly, interest should be placed in better informing the role forest management plays in enhancing resilience and adaptive capacity to future climate conditions and how that affects carbon storage, forest structural characteristics and in turn, carbon permanence, additionality, leakage, and the forest bioeconomy.

Together these research priority areas address some of the critical gaps across carbon science, methodologies, policy, and management to support high-integrity forest carbon credits. Going forward, there is a continued need to identify cross-cutting research priorities that span all priority areas highlighting the interactions between them noting that a greater need for transparency and advances in technologies, were a reoccurring theme of this review. Advancing how high-integrity is defined with regards to credits, iterating upon those efforts, and better linking understanding of what constitutes high-integrity to forest carbon topics, with particularly emphasis on the science, management, and policy, will serve to improve how carbon markets function, reduce global GHG emissions, and develop forest carbon credits resulting in positive outcomes for forest ecosystems and the societies that rely upon them. Investments in these areas could substantially improve the ability of land managers, carbon project developers, and decision-makers to make better informed, data-driven decisions that align with climate mitigation goals, society well-being, and other sustainable forest management goals.

Conclusions

Carbon projects and markets are highly complex, and there is no single solution to the issues facing them. This collaborative paper has laid out potential priorities to advance the implementation of carbon projects to generate high-integrity forest carbon credits by discussing key points where further research and cross sector collaboration can improve existing frameworks leading to better outcomes. Continued research on improving quantification methods, establishing safeguards to protect local communities and environments, increased public engagement, and advancing public–private partnerships may help address key gaps and needs in the field. Improving the integrity of carbon credits serves to support climate mitigation goals, economic health of natural resource dependent communities, and advance the underlying science of carbon quantification and forest management. This paper outlined priorities areas identified to address current limitations impacting the integrity of forest carbon projects. Furthermore, continued knowledge sharing and knowledge co-production amongst academics and across industry could help address the needs posed in this paper.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s44392-026-00111-x>.

Acknowledgements We thank all participants of the 2025 Forest + Climate Learning Exchange Series (Appendix B). We gratefully acknowledge Rebecca Sanders-DeMott from the Clean Air Task Force for her contributions to the discussion and her valuable feedback on this manuscript. Funding for this work was supported in part by The Society of American Forester Hagenstein Fund and the U.S. Department of Agriculture, Forest Service for Chizmar's time.

Author Contributions Conceptualization: M Kreye, C Papa. Data curation: M Kreye, C Papa, S Widderich, E Beresford. Formal analysis, investigation, methodology: M Kreye, C Papa, S Widderich, E Beresford, W Anderegg, E Belair, S Chizmar, T Cushing, A Daigneault, M Fernandez, C Galik, J Gibson, J Gunn, B Haya, D Hayes, M Hurteau, L Kaarakka, T Kowalczyk, G Latta, D McEvoy, K Novick, R Pokharel, T Ruseva, B Sohngen, J Stanton. Writing—original draft: M Kreye, C Papa, S Widderich, E Beresford. Writing—review & editing: M Kreye, C Papa, S Widderich, E Beresford, W Anderegg, E Belair, S Chizmar, T Cushing, A Daigneault, M Fernandez, C Galik, J Gibson, J Gunn, B Haya, D Hayes, M Hurteau, L Kaarakka, T Kowalczyk, G Latta, D McEvoy, K Novick, R Pokharel, T Ruseva, B Sohngen, J Stanton. Project Administration: M Kreye, C Papa. Supervision: M Kreye, C Papa. Funding Acquisition: M Kreye, C Papa.

Data Availability No data availability statement is required, as this review did not generate or analyze any new datasets.

Declarations

Competing interests The authors declare no conflicts of interests or competing interests, and the findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line

to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Agbakwuru, V., O. B. Onyenahazi, B. O. Antwi, and K. Oyewale. 2024. The impact of environmental, social, and governance (ESG) reporting on corporate financial performance. *International Journal of Research Publication and Reviews* 5 (9): 3629–3644. <https://doi.org/10.55248/gengpi.5.0924.2710>.
- Aggarwal, A. 2020. Revisiting the land use assumptions in forest carbon projects through a case from India. *Journal of Environmental Management* 267:110673. <https://doi.org/10.1016/j.jenvman.2020.110673>.
- Altman, J., P. Fibich, V. Trotsiuk, and N. Altmanova. 2024. Global pattern of forest disturbances and its shift under climate change. *Science of the Total Environment* 915 : 170117. <https://doi.org/10.1016/j.scitotenv.2024.170117>.
- Anderegg, W. R., L. Blanchard, C. Anderson, G. Badgley, D. Cullenward, P. Gao, M. L. Goulden, B. Haya, J. A. Holm, M. D. Hurteau, and M. Lague. 2025a. Towards more effective nature-based climate solutions in global forests. *Nature* 643 (8074): 1214–1222. <https://doi.org/10.1038/s41586-025-09116-6>.
- Anderegg, W. R., A. T. Trugman, G. Vargas G, C. Wu, and L. Yang. 2025b. Current forest carbon offset buffer pool contributions do not adequately insure against disturbance-driven carbon losses. *Global Change Biology* 31 (6): e70251. <https://doi.org/10.1111/gcb.70251>.
- Anderson-Teixeria, K. J., and E. P. Belair. 2021. Effective forest-based climate change mitigation requires our best science. *Global Change Biology* 28 (4): 1200–1203. <https://doi.org/10.1111/gcb.16008>.
- Arodudu, O., O. Therasme, T. Volk, R. Malmshiemer, P. Crovella, R. Germain, D. Kloster, and D. Kumar. 2023. Towards a carbon accounting framework for assessing the benefits of biogenic wood carbon to net zero carbon targets. *Forests* 14 (10): 1959. <https://doi.org/10.3390/f14101959>.
- Badgley, G., J. Freeman, J. J. Hamman, B. Haya, A. T. Trugman, W. R. L. Anderegg, and D. Cullenward. 2021. Systematic over-crediting in California's forest carbon offsets program. *Global Change Biology* 28 (4): 1433–1445. <https://doi.org/10.1111/gcb.15943>.
- Badgley, G., F. Chay, O. S. Chegwidden, J. J. Hamman, J. Freeman, and D. Cullenward. 2022. California's forest carbon offsets buffer pool is severely undercapitalized. *Frontiers in Forests and Global Change* 5 : 930426. <https://doi.org/10.5281/zenodo.6465433>.
- Bagstad, K. J., D. J. Semmens, S., Waage, and R. Winthrop. 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. *Ecosystem Services* 5: 27–39. <https://doi.org/10.1016/j.ecoser.2013.07.004>.
- Balmford, A., P. H. S. Brancalion, D. Coomes, B. Filewod, B. Groom, A. Guizar-Coutino, J. P. G. Jones, S. Keshav, A. Kontoleon, A. Madhavapeddy, Y. Malhi, E. O. Sills, B. B. N. Strassburg, F. Venmans, T. A. P. West, C. Wheeler, and T. Swinfield. 2023. Credit credibility threatens forests. *Science* 380 (6644): 466–467. <https://doi.org/10.1126/science.adh3426>.
- Bento, A., R. Kanbur, and B. Leard. 2016. On the importance of baseline setting in carbon offsets markets. *Climatic Change* 137 (3): 625–637. <https://doi.org/10.1007/s10584-016-1685-2>.
- Bhaduri, S., Biddy, Q., Elliott, C. H., Jacobs, J., Rummel, M., Ristvey, J., ... and M. Recker. 2022. Co-designing a rural research practice partnership to design and support STEM pathways for rural youth. *Theory & Practice in Rural Education* 12(2). <https://doi.org/10.3776/tpr.2022.v12n2p45-70>
- Birdsey, R., P. Duffy, C. Smyth, W. A. Kurz, A. J. Dugan, and R. Houghton. 2018. Climate, economic, and environmental impacts of producing wood for bioenergy. *Environmental Research Letters* 13 (5): 050201. <https://doi.org/10.1088/1748-9326/aab9d5>.
- Bonan, G. B. 2008. Forest and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* 320:1444–14449. <https://doi.org/10.1126/science.1155121>.
- Borsah, A.A., M., Nazeer, and M.S. Wong. 2023. LIDAR-based forest biomass remote sensing: a review of metrics methods and assessment criteria for the selection of allometric equations. *Forests* 14 (10): 2095. <https://doi.org/10.3390/f14102095>.

- Breshani, E. 2025. Understanding CBAM: Past, present, and future. Clear Blue Markets. January, 2024. Accessed at: <https://www.clearbluemarkets.com/knowledge-base/understanding-cbam-past-present-and-future>
- Bubser, D., Fernholz, K., and E. Meyer. 2023. Concept paper: Exploring the potential effects of an expanding forest carbon market on working forests and communities in the United States. Camibus Consulting and Dovetail Partners, December 2023. Accessed at: <https://www.dovetailinc.org/upload/tmp/1703195421.pdf>
- Buma, B., D. R. Gordon, K. M. Kleisner, A. Bartuska, A. Bidlack, R. DeFries, P. Ellis, P. Friedlingstein, S. Metzger, G. Morgan, and K. Novick. 2024. Expert review of the science underlying nature-based climate solutions. *Nature Climate Change* 14 (4): 402–406. <https://doi.org/10.1038/s41558-024-01960-0>.
- Busby, G., and C.S. Binkley. 2021. Explaining the disconnect between lumber and timber prices. Nuveen Natural Capital Opinion Piece. Accessed at: <https://www.nuveen.com/global/insights/alternatives/explaining-the-disconnect-between-lumber-and-timber-prices>
- Cadman, T. 2013. Applying an Empirical Evaluation to the Governance Legitimacy of Carbon Offset Mechanisms on the Basis of Stakeholder Perceptions. In: Cadman, T. (eds) Climate Change and Global Policy Regimes. International Political Economy. Palgrave Macmillan, London. https://doi.org/10.1057/9781137006127_6
- Caldwell, P.V., K.L. Martin, J.M. Vose, J.S. Baker, T.W. Warziniack, J.K. Costanza, G.E. Frey, A., Nehra, and C.M. Mihai. 2023. Forested watersheds provide the highest water quality among all land cover types, but the benefit of this ecosystem service depends on landscape context. *Science of The Total Environment* 882: 163550. <https://doi.org/10.1016/j.scitotenv.2023.163550>
- Cameron, I., Austen, C., Davie, N., Knoedler-Thoma, F., Lewis, D., Lockhart, J., McClean, R., Richter A., Tustin, M., Welstead, F., White A., Brancato, D., Russell, M., Shirley A., Hughes, C., Bull, R., and J. Adamson. 2024. Impact of carbon markets on the rural economy, 1st edition. Eds: Birch, S. Royal Institution of Chartered Surveyors (RICS), London. Accessed at: https://www.rics.org/content/dam/ricsglobal/documents/standards/Impact-of-carbon-markets-on-the-rural-economy-UK_Nov2024.pdf
- Caperon, L., McEachan, R.R., Endacott, C., and S.M. Ahern. 2022. Evaluating community co-design, maintenance and ownership of green spaces in underserved communities using participatory research. *Journal of Participatory Research Methods*, 3(1). <https://doi.org/10.35844/001c.35632>
- Carbon Plan 2024. California's Shrinking Buffer Pool. Accessed at: <https://carbonplan.org/blog/carbon-buffer-decline>
- Carovillano, C. 2025. Prioritizing wildlife habitat in maine's commercial forest landscapes: A bioeconomic modeling analysis of ecosystem service provisions under future management pathways. Master's thesis, University of Maine. Accessed at: <https://digitalcommons.library.umaine.edu/etd/4139/>
- Chan, K. M. A., A. D. Guerry, P. Balvanera, S. Klain, T. Satterfield, X. Basurto, A. Bostrom, R. Chuenpagdee, R. Gould, B. S. Halpern, N. Hannahs, J. Levine, B. Norton, M. Ruckelshaus, R. Russell, J. Tam, and U. Woodside. 2012. Where are cultural and social in ecosystem services? A framework for constructive engagement. *BioScience* 62 (8): 744–756. <https://doi.org/10.1525/bio.2012.62.8.7>.
- Climate Impact Partners. 2024. Quite Climate Action: How climate actions and commitments are holding strong despite deadlines coming into focus and scrutiny rising around definitions. Fortune Global 500 Report. September 2024. Access at: <https://www.climateimpact.com/news-insights/fortune-global-500-climate-commitments/fg500-2024-report/>
- Coffield, S. R., C. D. Vo, J. A. Wang, G. Badgley, M. L. Goulden, D. Cullenward, W. R. L. Anderegg, and J. T. Randerson. 2022. Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. *Global Change Biology* 28 (22): 6789–6806. <https://doi.org/10.1111/gcb.16380>.
- Cook-Patton, S. C., D. Shoch, and P. W. Ellis. 2021. Dynamic global monitoring needed to use restoration of forest cover as a climate solution. *Nature Climate Change* 11 (5): 366–368. <https://doi.org/10.1038/s41558-021-01022-9>.
- Cubas-Baez, A., W. Sunderlin, A. M. Larson, and A. Frechette. 2025. From promises to practice: Persistent challenges in safeguarding local rights in forest carbon market initiatives. *CABI Reviews* 20 (1): 0025. <https://doi.org/10.1079/cabireviews.2025.0025>.
- D'Amato, A. W., J. B. Bradford, S. Fraver, and B. J. Palik. 2011. Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. *Forest Ecology and Management* 262 (5): 803–816. <https://doi.org/10.1016/j.foreco.2011.05.014>.

- Daigneault, A., B. Sohngen, E. Belair, and P. Ellis. 2025. A globally relevant data-driven assessment of carbon leakage from forestry. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/ae0ce2>.
- Daigneault, A., Daniel J. Hayes, Ivan J. Fernandez, and Aaron R. Weiskittel. 2022. Forest Carbon Accounting and Modeling Framework Alternatives: An Inventory, Assessment, and Application Guide for Eastern US State Policy Agencies. Final Report. <https://doi.org/10.13140/RG.2.2.24014.33603>
- de Roucy-Rochegonde, L., and Buffard, A. (2025). AI, Data Centers and Energy Demand: Reassessing and Exploring the Trends. Ifri Papers, The French Institute of International Relations, February 2025. https://www.ifri.org/sites/default/files/2025-02/ifri_buffard-rochegonde_ai_data_centers_energy_2025_2.pdf
- Deal, R. L., B. Cochran, and G. LaRocco. 2012. Bundling of ecosystem services to increase forestland value and enhance sustainable forest management. *Forest Policy and Economics* 17:69–76. <https://doi.org/10.1016/j.forpol.2011.12.007>.
- Dhond, A., zu Ermgassen, S., Swinfield, T., Robertson, M., Heinemeyer, A., Owen, S., and J.W. Bull. 2026. Pervance Risks to Biodiversity and Nature-Based Carbon Offsets, 19(2), e70044. <https://doi.org/10.1111/con4.70044>
- Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R.T., Molnár, Z., ... and Y. Shirayama. 2018. Assessing nature's contributions to people. *Science*, 359(6373), 270–272. <https://doi.org/10.1126/science.aap8826>
- Diedrich, G., and K. Clay. 2025. Navigating dual enrollment: Assessing compatibility between improved management carbon offset projects and preferential property tax programs across nine states. *Journal of Sustainable Forestry* 44 (7): 655–678. <https://doi.org/10.1080/10549811.2025.2527756>.
- Donatti, C. I., A. Andrade, E. Cohen-Shacham, G. Fedele, X. Hou-Jones, and B. Robyn. 2022. Ensuring that nature-based solutions for climate mitigation address multiple global challenges. *One Earth* 5 (5): P493–504. <https://doi.org/10.1016/j.oneear.2022.04.010>.
- Doraisami, M., G. M. Domke, and A. R. Martin. 2024. Improving wood carbon fractions for multiscale forest carbon estimation. *Carbon Balance and Management* 19 (1): 25. <https://doi.org/10.1186/s13021-024-00272-2>.
- Dye, A. W., R. M. Houtman, P. Gao, W. R. L. Anderegg, C. J. Fettig, J. A. Hicke, J. B. Kim, C. J. Still, K. Young, and R. L. Riley. 2024. Carbon, climate, and natural disturbance: A review of mechanisms, challenges, and tools for understanding forest carbon stability in an uncertain future. *Carbon Balance and Management*. <https://doi.org/10.1186/s13021-024-00282-0>.
- Eastman, B., Brzostek, E., Cifelli, D., Gazal, K., Kannenberg, S.A., Keck, M., ... and G. Schwartzman. 2025. Building trust and efficacy in forest carbon programs: lessons from stakeholder engagement in Central Appalachia. *BioScience*, 75(10), 865–880. <https://doi.org/10.1093/biosci/biaf098>
- Elias, M., E. Yackulic, K. Duffy, P. Saks, D. L. Sanchez, N. Pevzner, S. Plumb, J. Dyszynski, and C. Bracer. 2025. Carbon finance for forest resilience in California. *Frontiers in Forests and Global Change* 7:1507554. <https://doi.org/10.3389/ffgc.2024.1507554>.
- FAO. 2025. Global Forest Resources Assessment 2025. Rome. <https://doi.org/10.4060/cd6709en>
- Fargione, J.E., Bassett, S., Boucher, T., Bridgham, S.D., Conant, R.T., Cook-Patton, S.C., ... and B.W. Griscom. 2018. Natural climate solutions for the United States. *Science advances*, 4(11), eaat1869. <https://doi.org/10.1126/sciadv.aat1869>
- Farjana, S. H., and M. Ashraf. 2025. Developing the conceptual framework for the key performance indicators for sustainable wood waste supply chain. *Environment, Development and Sustainability* 27 (3): 6921–6944. <https://doi.org/10.1007/s10668-023-04174-0>.
- Filewod, B., and G. McCarney. 2023. Avoiding carbon leakage from nature-based offsets by design. *One Earth* 6 (7): 790–802. <https://doi.org/10.1016/j.oneear.2023.05.024>.
- Fisher, R.A., Koven, C.D., Anderegg, W.R.L., Christoffersen, B.O., Dietze, M.C., Farrior, C.E., Holm, J.A., Hurtt, G.C., Knox, R.G., Lawrence, P.J., Lichstein, J.W., Longo, M., Matheny, A.M., Medvigy, D., Muller-Landau, H.C., Powell, T.L., Serbin, S.P., Sato, H., Shuman, J.K., ... and Moorcroft, P. R. 2018. Vegetation demographics in Earth System Models: A review of progress and priorities. *Global Change Biology* 24(1), 35–54. <https://doi.org/10.1111/gcb.13910>
- Forest Trends' Ecosystem Marketplace. 2025. State of the Voluntary Carbon Market 2025. Washington DC: Forest Trends Association. Accessed at: <https://www.ecosystemmarketplace.com/publications/2025-state-of-the-voluntary-carbon-market-sovcml/>
- Francis, E. J., P. Pourmohammadi, Z. L. Steel, B. M. Collins, and M. D. Hurteau. 2023. Proportion of forest area burned at high-severity increases with increasing forest cover and connectivity

- in western US watersheds. *Landscape Ecology* 38 (10): 2501–2518. <https://doi.org/10.1007/s10980-023-01710-1>.
- Galik, C. S., and R. B. Jackson. 2009. Risks to forest carbon offset projects in a changing climate. *Forest Ecology and Management* 257:2209–2216. <https://doi.org/10.1016/j.foreco.2009.03.017>.
- Galik, C. S., B. C. Murray, S. Mitchell, and P. Cottle. 2016. Alternative approaches for addressing non-permanence in carbon projects: An application to afforestation and reforestation under the Clean Development Mechanism. *Mitigation and Adaptation Strategies for Global Change* 21 (1): 101–118. <https://doi.org/10.1007/s11027-014-9573-4>.
- Galik, C. S., J. S. Baker, A. Daigneault, and G. Latta. 2022. Crediting temporary forest carbon: Retrospective and empirical perspectives on accounting options. *Frontiers in Forests and Global Change* 5:933020. <https://doi.org/10.3389/ffgc.2022.933020>.
- Gan, J., and B. A. McCarl. 2007. Measuring transnational leakage of forest conservation. *Ecological Economics* 64 (2): 423–432. <https://doi.org/10.1016/j.ecolecon.2007.02.032>.
- Gazal, K., B. Eastman, S. Cheye, K. Arano, and G. Dahle. 2025. Understanding family forest landowners' preferences for carbon offset programs in Central Appalachia. *Forests* 16 (9): 1415. <https://doi.org/10.3390/f16091415>.
- Ghosh, D., D. S. Page-Dumroese, H.-S. Han, and N. Anderson. 2025. Role of biochar made from low-value woody forest residues in ecological sustainability and carbon neutrality. *Soil Science Society of America Journal* 89 (1): e20793. <https://doi.org/10.1002/saj2.20793>.
- Hanssen, S.v., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., Van Vurren, D.P., and M.A.J. Huijbregts. 2020. The climate change mitigation potential of bioenergy with carbon capture and storage. *Nature Climate Change* 10, 1023–1029. <https://doi.org/10.1038/s41558-020-0885-y>.
- Haya, B. K., S. Evans, L. Brown, J. Bukoski, V. Butsic, B. Cabiyo, R. Jacobson, A. Kerr, M. Potts, and D. L. Sanchez. 2023. Comprehensive review of carbon quantification by improved forest management offset protocols. *Frontiers in Forests and Global Change* 6:958879. <https://doi.org/10.3389/ffgc.2023.958879>.
- He, M., M. Smidt, W. Li, and Y. Zhang. 2021. Logging industry in the United States: Employment and profitability. *Forests* 12 (12): 1720. <https://doi.org/10.3390/f12121720>.
- Healey, S. P., Z. Yang, A. M. Erb, R. M. Bright, G. M. Domke, T. S. Frescino, and C. B. Schaaf. 2025. Enhanced observation of forest albedo reveals significant offsets to reported carbon benefits. *Environmental Research Letters* 20 (7): 074025. <https://doi.org/10.1088/1748-9326/add60a>.
- Honegger, M., A. Michaelowa, and J. Roy. 2021. Potential implications of carbon dioxide removal for the sustainable development goals. *Climate Policy* 21 (5): 678–698. <https://doi.org/10.1080/14693062.2020.1843388>.
- Hurteau, M. D., C. G. Jung, E. J. Francis, S. Dobrowski, C. Littlefield, and S. A. Parks. 2025. Decreasing landscape carbon storage in western US forests with 2° C of warming. *Environmental Research: Ecology* 4 (4): 041001. <https://doi.org/10.1088/2752-664X/ae212c>.
- ICVCM. 2025. CCP-approved methodologies. Accessed at: <https://icvcm.org/knowledge-resources/ccp-approved-methodologies/>.
- 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, 35-115, <https://doi.org/10.59327/IPCC/AR6-9789291691647>.
- Johnson, L. K., M. J. Mahoney, G. M. Domke, and C. M. Beier. 2025. New allometric models for the USA create a shift in forest carbon estimation, modeling, and mapping. *Forest Ecology and Management* 589:122751. <https://doi.org/10.1016/j.foreco.2025.122751>.
- Kallio, I. A. M., and B. Solberg. 2018. Leakage of forest harvest changes in a small open economy: case Norway. *Scandinavian Journal of Forest Research* 33 (5): 502–510. <https://doi.org/10.1080/02827581.2018.1427787>.
- Kerchner, C. D., and W. S. Keeton. 2015. California's regulatory forest carbon market: Viability for northeast landowners. *Forest Policy and Economics* 50:70–81. <https://doi.org/10.1016/j.forpol.2014.09.005>.
- Khanal, P. N., D. L. Grebner, I. A. Munn, S. C. Grado, R. K. Grala, and J. E. Henderson. 2017. Evaluating non-industrial private forest landowner willingness to manage for forest carbon sequestration in the southern United States. *Forest Policy and Economics* 75:112–119. <https://doi.org/10.1016/j.forpol.2016.07.004>.
- Knott, J.A., Liknes, G.C., Giebink, C.L., Oh, S., Domke, G.M., McRoberts, R.E., ... and B.F. Walters. 2023. Effects of outliers on remote sensing-assisted forest biomass estimation: A case study from

- the United States national forest inventory. *Methods in Ecology and Evolution* 14(7): 1587–1602. <https://doi.org/10.1111/2041-210X.14084>
- Korner, C. 2026. Conceptual pitfalls in the forest carbon debate. *Carbon Balance and Management* 21(59). <https://doi.org/10.1186/s13021-026-00412-w>
- Kowler, L. F., A. K. Pratihast, Perez Ojeda, A. del Arco, A. M. Larson, C. Braun, and M. Herold. 2020. Aiming for sustainability and scalability: community engagement in forest payment schemes. *Forests* 11:444. <https://doi.org/10.3390/f11040444>.
- Kreibich, N., and L. Hermwille. 2021. Caught in between: Credibility and feasibility of the voluntary carbon market post-2020. *Climate Policy* 21 (7): 939–957. <https://doi.org/10.1080/14693062.2021.1948384>.
- Lamichhane, S., R. Parajuli, J. D. Henderson, B. Kanieski da Silva, and S. M. Tanger. 2025. Examining divergence in softwood lumber and timber prices in the southern United States. *Forest Science* 71:183–202. <https://doi.org/10.1007/s44391-024-00012-6>.
- Lecina-Diaz, J., J. Martínez-Vilalta, A. Alvarez, J. Vayreda and J. Retana. 2021. Assessing the risk of losing forest ecosystem services due to wildfires. *Ecosystems* 24 (7): 1687–1701. <https://doi.org/10.1007/s10021-021-00611-1>.
- Lehmann, J., A. Cowie, C. A. Masiello, C. Kammann, D. Woolf, J. E. Amonette, M. L. Cayuela, M. Camps-Arbestain, and T. Whitman. 2021. Biochar in climate change mitigation. *Nature Geoscience* 14:883–892. <https://doi.org/10.1038/s41561-021-00852-8>.
- Lenton, T. M., C. Xu, J. F. Abrams, A. Ghadiali, S. Loriani, B. Sakschewski, C. Zimm, K. L. Ebi, R. R. Dunn, J.-C. Svenning, and M. Scheffer. 2023. Quantifying the human cost of global warming. *Nature Sustainability* 6:1237–1247. <https://doi.org/10.1038/s41893-023-01132-6>.
- Levesque, C. 2024. Timber Harvest Levels tell a Striking Story. Northern Logger Magazine, April 2024. Accessed at: <https://www.northernlogger.com/northern-logger-magazine/timber-harvest-levels-tell-a-striking-story/>
- Li, Y. 2026. Timber situation and 2026 outlook. In Georgia Ag Forecast (AP 130-4-13). University of Georgia Cooperative Extension. Accessed at: <https://fieldreport.caes.uga.edu/publications/AP130-4-13/2026-timber-forecast/>
- Lim, H., Medvigy, D., Mäkelä, A., Kim, D., Albaugh, T.J., Knier, A., ... and R. Oren. 2024. Overlooked branch turnover creates a widespread bias in forest carbon accounting. *PNAS* 121(42): e2401035121. <https://doi.org/10.1073/pnas.2401035121>
- Lin, B. B., S. Macfadyen, A. R. Renwick, S. A. Cunningham, and N. A. Schellhorn. 2013. Maximizing the environmental benefits of carbon farming through ecosystem service delivery. *BioScience* 63 (10): 793–803. <https://doi.org/10.1525/bio.2013.63.10.6>.
- Lofqvist, S., R. D. Garrett, and J. Ghazoul. 2023. Incentives and barriers to private finance for forest landscape restoration. *Nature Ecology & Evolution* 7:707–715. <https://doi.org/10.1038/s41559-023-02037-5>.
- Ludvig, A., B. Schmid, B. Ollerer, L. Nikinmaa, P. Hurtado, M. Rodriguez-Ogea, and A. Toppinen. 2024. Increasing climate-related resilience in the forest-based value chains? A policy perspective. *Forest Policy and Economics* 168:103314. <https://doi.org/10.1016/j.forpol.2024.103314>.
- Mansuy, N., J. Barrette, J. Laganriere, W. Mabee, D. Pare, S. Gautam, E. Thiffault, and S. Ghafghazi. 2018. Salvage harvesting for bioenergy in Canada: From sustainable and integrated supply chain to climate chain mitigation. *Wires Energy and Environment* 7 (5): e298. <https://doi.org/10.1002/wene.298>.
- Maron, M., A. von Hase, F. Quetier, L. J. Sonter, S. Theis, and S. O. S. E. zu Ermgassen. 2025. Biodiversity offsets, their effectiveness and their role in a nature positive future. *Nature Reviews Biodiversity*. <https://doi.org/10.1038/s44358-025-00023-2>.
- Mathur, V. N., S. Afonis, J. Paavola, A. J. Dougill, and L. C. Stringer. 2013. Experience of host communities with carbon market projects: Towards multi-level climate justice. *Climate Policy* 14 (1): 42–62. <https://doi.org/10.1080/14693062.2013.861728>.
- Matthews, H. D., K. Zickfeld, M. Dickau, A. J. MacIsaac, S. Mathesius, C. M. Nzotungicimpaye, and A. Luers. 2022. Temporary nature-based carbon removal can lower peak warming in a well-below 2 C scenario. *Communications Earth & Environment* 3 (1): 65. <https://doi.org/10.1038/s43247-022-00391-z>.
- Matthews, H. D., K. Zickfeld, A. Koch, and A. Luers. 2023. Accounting for the climate benefit of temporary carbon storage in nature. *Nature Communications* 13:5485. <https://doi.org/10.1038/s41467-023-41242-5>.

- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: synthesis*. Island Press, Washington, DC.
- Moioli, C., L. Drouet, D. Roeser, J. Emmerling, and H. Zerriffi. 2025. Mitigation deterrence and unrealistic expectations: The future costs of forest carbon offsets. *Global Environmental Change* 95:103068. <https://doi.org/10.1016/j.gloenvcha.2025.103068>.
- Munro, H. L., C. W. Woodall, W. R. L. Anderegg, J. W. Atkins, C. M. Beier, B. P. Bullock, et al. 2025. Challenges and strategic recommendations for enhancing quantification and projection of forest carbon dynamics. *Journal of Forestry* 123:703–734. <https://doi.org/10.1007/s44392-025-00048-7>.
- Nagel, L. M., M. K. Janowiak, P. W. Clark, C. L. Peterson, M. R. Vicini, B. J. Palik, A. W. D'Amato, M. A. Battaglia, and C. W. Swanston. 2026. Ten years of adaptive silviculture for climate change: An applied, coproduced experimental framework. *Bioscience* 76 (2): 157–170. <https://doi.org/10.1093/biosci/biaf170>.
- Nolan, C. J., C. B. Field, and K. J. Mach. 2021. Constraints and enablers for increasing carbon storage in the terrestrial biosphere. *Nature Reviews Earth & Environment* 2 (6): 436–446. <https://doi.org/10.1038/s43017-021-00166-8>.
- Novick, K., S. Metzger, W. R. L. Anderegg, M. Barnes, D. S. Cala, K. Guan, K. S. Hemes, D. Y. Hollinger, J. Kumar, M. Litvak, D. Lombardozzi, C. P. Normile, P. Oikawa, B. R. K. Runkle, M. Torn, and S. Wiesner. 2022. Informing nature-based climate solutions for the United States with the best-available science. *Global Change Biology* 28 (12): 3778–3794. <https://doi.org/10.1111/gcb.16156>.
- Novick, K. A., T. F. Keenan, W. R. L. Anderegg, C. P. Normile, B. R. K. Runkle, E. E. Oldfield, G. Shrestha, D. D. Baldocchi, M. E. K. Evans, J. T. Randerson, J. Sanderman, M. S. Tom, A. T. Trugman, and C. A. Williams. 2024a. We need a solid scientific basis for nature-based climate solutions in the United States. *PNAS* 121 (14): e2318505121. <https://doi.org/10.1073/pnas.2318505121>.
- Novick, K. A., T. F. Keenan, W. R. L. Anderegg, C. P. Normile, B. R. K. Runkle, E. E. Oldfield, G. Shrestha, D. D. Baldocchi, M. E. K. Evans, J. T. Randerson, J. Sanderman, M. S. Tom, A. T. Trugman, and C. A. Williams. 2024. We need a solid scientific basis for nature-based climate solutions in the United States. *PNAS* 121 (14): e2318505121. <https://doi.org/10.1073/pnas.2318505121>.
- Novick, K.A., Keenan, T.F., Moore, D.J., Phillips, R.P. and M. Barnes. 2024b. Addressing, and reducing, bias in estimates of forest carbon removal. *AGU Fall Meeting 2024*, held in Washington, D.C., 9–13 December 2024, Session: Global Environmental Change / Connecting Science and Monitoring, Reporting, and Verification (MRV) Development for Cross-Pathway Carbon Dioxide Removal (CDR) Technologies I Oral, id. GC31B-03
- Olawade, D. B., O. Z. Wada, A. C. David-Olawade, O. Fapohunda, A. O. Ige, and J. Ling. 2024. Artificial intelligence potential for net zero sustainability: Current evidence and prospects. *Next Sustainability* 4:100041. <https://doi.org/10.1016/j.nxsust.2024.100041>.
- Palik, B. J., A. W. D'Amato, J. F. Franklin, and K. N. Johnson. 2020. *Ecological silviculture: Foundations and applications*. Waveland Press.
- Pan, W., M.-K. Kim, Z. Ning, and H. Yang. 2020. Carbon leakage in energy/forest sectors and climate policy implications using meta-analysis. *Forest Policy and Economics* 115:102161. <https://doi.org/10.1016/j.forpol.2020.102161>.
- Pan, Y., R. A. Birdsey, O. L. Phillips, R. A. Houghton, J. Fang, P. E. Kauppi, H. Keith, et al. 2024. The enduring world forest carbon sink. *Nature* 631:563–569. <https://doi.org/10.1038/s41586-024-07602-x>.
- Pan, C., Shrestha, A., Innes, J.L., Zhou, G., Li, N., Li, J., ... and G. Wang. (2022). Key challenges and approaches to addressing barriers in forest carbon offset projects. *Journal of Forestry Research* 33(4):1109–1122. <https://doi.org/10.1007/s11676-022-01488-z>
- Parisa, Z., E. Marland, B. Sohngen, G. Marland, and J. Jenkins. 2022. The time value of carbon storage. *Forest Policy and Economics* 144:102840. <https://doi.org/10.1016/j.forpol.2022.102840>.
- Premeir, M., Simons-Legaard, E., Daigneault, A., Hayes, D., Solarik, K.A., and A. Weiskittel. 2025. Some models are useful... for estimating standing aboveground carbon in US Forests. *Journal of Forestry* 1–30. <https://doi.org/10.1007/s44392-025-00056-7>
- Quegan, S., T. Le Toan, J. Chave, J. Dall, J.-F. Exbrayat, D. H. T. Minh, M. Lomas, M. M. D'Alessandro, P. Paillou, K. Papathanassiou, F. Rocca, S. Saatchi, K. Scipal, H. Shugart, T. L. Smallman, M. J. Soja, S. Tebaldini, L. Ulander, L. Villard, and M. Williams. 2019. The European Space Agency BIOMASS mission: Measuring forest above-ground biomass from space. *Remote Sensing of Environment* 227:44–60. <https://doi.org/10.1016/j.rse.2019.03.032>.

- Rana, P., F. Fleischman, and A. Sharma. 2026. Why carbon offsets may fail in complex systems: A causal inference perspective. *Environmental Science and Policy* 176:104325. <https://doi.org/10.1016/j.envsci.2026.104325>.
- Randazzo, N. A., D. R. Gordon, and S. P. Hamburg. 2023. Improved assessment of baseline and additionality for forest carbon crediting. *Ecological Applications* 33 (3): e2817. <https://doi.org/10.1002/eap.2817>.
- Restrepo, H.I., Munro, H.L., Prisley, S.P., Schilling, E., Radtke, P.J., Bush, R., ... and C.W. Woodall. 2025. Population estimate differences for forest biomass, merchantable volume, and carbon pools as a result of modeling system updates in the United States. *Forest Ecology and Management* 595: 122965. <https://doi.org/10.1016/j.foreco.2025.122965>
- Reis, G., and S. Evans. 2025. Resilient Growth in US Forest Carbon Markets. *Fastmarkets*. <https://www.fastmarkets.com/insights/resilient-growth-in-us-forest-carbon-markets/>.
- Richards, K., and K. Andersson. 2001. The leaky sink: Persistent obstacles to a forest carbon sequestration program based on individual projects. *Climate Policy* 1 (1): 41–54. [https://doi.org/10.1016/S1469-3062\(00\)00003-6](https://doi.org/10.1016/S1469-3062(00)00003-6).
- Richards, K. R., and G. E. Huebner. 2012. Evaluating protocols and standards for forest carbon-offset programs, part A: Additionality, baselines and permanence. *Carbon Management* 3 (4): 393–410. <https://doi.org/10.4155/cmt.12.38>.
- Romm, J., S. Lezak, and A. Alshamsi. 2025. Are carbon offsets fixable?. *Annual Review of Environment and Resources* 50(1): 649–680. <https://doi.org/10.1146/annurev-environ-112823-064813>.
- Roshani, H. S., P. Kumar, M. Masroor, M. J. Rahaman, S. Rehman, R. Ahmed, and M. Sahana. 2022. Forest vulnerability to climate change: A review for future research framework. *Forests* 13 (6): 917. <https://doi.org/10.3390/f13060917>.
- Runkle, B. R. K. 2022. Review: Biological engineering for nature-based climate solutions. *Journal of Biological Engineering* 16:7. <https://doi.org/10.1186/s13036-022-00287-8>.
- Russell, M. B., C. J. Chamberlain, L. Riley, N. A. Mushegian, J. S. Gunn, E. P. Belair, and S. U. Busby. 2025. Characterizing timber harvest occurrence and intensity to inform forest carbon management across the eastern United States. *Frontiers in Forests and Global Change* 8:1594324. <https://doi.org/10.17615/n9b2-3432>.
- Sanders-DeMott, R., Hutyra, L.R., Hurteau, M.D., Keeton, W. S., Fallon, K.S., Anderegg, W.R.L., ... and W.S. Walker. 2025. Ground-truth: Can forest carbon protocols ensure high-quality credits?. *Earth's Future* 13(5): e2024EF005414. <https://doi.org/10.1029/2024EF005414>
- Sass, E. M., M.-L. Marla, J. B. Brett, C. Jesse, H. Andrew, H. Emily, and R. Amanda. 2021. Dynamics of large corporate forestland ownerships in the United States. *Journal of Forestry* 119:363–375. <https://doi.org/10.1093/jofore/fvab013>.
- Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., ... and B. Turner. 2021. Getting the message right on nature-based solutions to climate change. *Global Change Biology* 27(8):1518–1546. <https://doi.org/10.1111/gcb.15513>
- Seidl, R., D. Thom, M. Kautz, D. Martin-Bentio, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M. J. Lexer, V. Trotsiuk, P. Mariota, M. Svoboda, M. Frabika, T. A. Nagel, and C. P. O. Reyser. 2017. *Forest Disturbance under Climate Change* 7:395–402. <https://doi.org/10.1038/nclimate3303>.
- Sharma, S., and M. M. Kreye. 2022. Forest owner willingness to accept payment for forest carbon in the United States: A meta-analysis. *Forests* 13 (9): 1346. <https://doi.org/10.3390/f13091346>.
- Smith, P., A. Arneth, D. K. A. Barnes, K. Ichii, P. A. Marquet, A. Popp, H.-O. Portner, A. D. Rogers, R. J. Scholes, B. Strassburg, J. Wu, and H. Ngo. 2022. How do we best synergize climate mitigation actions to co-benefit biodiversity. *Global Change Biology* 28 (8): 2555–2577. <https://doi.org/10.1111/gcb.16056>.
- Sohngen, B., and S. Brown. 2004. Measuring leakage from carbon projects in open economies: A stop timber harvesting project in Bolivia as a case study. *Canadian Journal of Forest Research* 34 (4): 829–839. <https://doi.org/10.1139/x03-249>.
- Soto, J. R., D. C. Adams, and F. J. Escobedo. 2016. Landowner attitudes and willingness to accept compensation from forest carbon offsets: Application of best–worst choice modeling in Florida USA. *Forest Policy and Economics* 63:35–42. <https://doi.org/10.1016/j.forpol.2015.12.004>.
- Stolz, N., and B. S. Probst. 2025. The negligible role of carbon offsetting in corporate climate strategies. *Nature Communications* 16:7963. <https://doi.org/10.1038/s41467-025-62970-w>.
- Sun, B., and B. Sohngen. 2009. Set-asides for carbon sequestration: Implications for permanence and leakage. *Climatic Change* 96 (3): 409–419. <https://doi.org/10.1007/s10584-009-9628-9>.

- Tedersoo, L., Sepping, J., Morgunov, A.S., Kiik, M., Esop, K., Rosenvald, R., ... and A. Antonelli. 2024. Towards a co-crediting system for carbon and biodiversity. *Plants, People, Planet* 6(1): 18–28. <https://doi.org/10.1002/ppp3.10405>
- Teo, H. C., N. H. L. Tan, Q. Zheng, A. J. Y. Lim, R. Sreekar, X. Chen, Y. Zhou, T. V. Sarira, J. D. T. De Alban, H. Tang, D. A. Friess, and L. P. Koh. 2023. Uncertainties in deforestation emission baseline methodologies and implications for carbon markets. *Nature Communications* 14:8277. <https://doi.org/10.1038/s41467-023-44127-9>.
- Tian, L., X. Wu, Y. Tao, M. Li, C. Qian, L. Liao, and W. Fu. 2023. Review of remote sensing-based methods for forest aboveground biomass estimation: Progress, challenges, and prospects. *Forests* 14 (6): 1086. <https://doi.org/10.3390/f14061086>.
- Trouwloon, D., C. Streck, T. Chagas, and G. Martinus. 2023. Understanding the use of carbon credits by companies: A review of the defining elements of corporate climate claims. *Global Challenges* 7 (4): 2200158. <https://doi.org/10.1002/gch2.202200158>.
- Urquhart, J., Ambrose-Oji, B., Chiswell, H., Courtney, P., Lewis, N., Powell, J., ... and C. Williams. 2023. A co-design framework for natural resource policy making: Insights from tree health and fisheries in the United Kingdom. *Land Use Policy* 134:106901. <https://doi.org/10.1016/j.landusepol.2023.106901>
- Van Kooten, G. C., and C. M. Johnston. 2016. The economics of forest carbon offsets. *Annual Review of Resource Economics* 8 (1): 227–246. <https://doi.org/10.1146/annurev-resource-100815-095548>.
- Vancley, F. 2017. Principles to gain a social licence to operate for green initiatives and biodiversity projects. *Current Opinion in Environmental Sustainability* 29:48–56. <https://doi.org/10.1016/j.cosust.2017.11.003>.
- Vaughan, D., C. Edgeley, and H. S. Han. 2022. Forest contracting businesses in the US southwest: Current profile and workforce training needs. *Journal of Forestry* 120 (2): 186–197. <https://doi.org/10.1093/jofore/fvab060>.
- Webb, J., Fujii, H., Rowlings, D., Grace, P., Mundree, S., Managi, S., and C. Wilson. 2025. Prospects for integration of carbon and biodiversity credits: an Australian case study review. *Sustainability Science* 1–14. <https://doi.org/10.1007/s11625-024-01603-5>
- Welden, E. A., A. Chausson, and M. S. Melanidis. 2021. Leveraging nature-based solutions for transformation: Reconnecting people and nature. *People and Nature* 3 (5): 966–977. <https://doi.org/10.1002/pan3.10212>.
- West, T. A. P., J. Borner, E. O. Sills, and A. Kontoleon. 2020. Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *PNAS* 117 (39): 24188–24194. <https://doi.org/10.1073/pnas.2004334117>.
- Woodall, C. W., H. L. Munro, J. W. Atkins, B. P. Bullock, T. R. Fox, C. M. Hoover, S. M. Kinane, L. T. Murray, S. P. Prisle, J. D. Shaw, and E. Smith-Mateja. 2025. Prioritizing opportunities to empower forest carbon decisions through strategic investment in forest modeling capacity. *Journal of Forestry* 123 (2): 241–262. <https://doi.org/10.1007/s44392-025-00012-5>.
- Wu, C., G. Badgley, M. L. Goulden, J. T. Randerson, A. T. Trugman, J. A. Wang, L. Yang, N. Acil, S. C. Cook-Patton, D. Cullenward, S. J. Davis, C. A. Williams, and W. R. L. Anderegg. 2026. Forest carbon protocols underestimate climate-driven carbon loss risks. *Nature*. <https://doi.org/10.1038/s41586-026-10571-y>.
- Xie, S.H., Kurz, W.A., and P.N. McFarlane. 2023. Substitution benefits of British Columbia's mitigation strategies in the bioeconomy. *Mitigation and Adaptation Strategies for Global Change* 28(18). <https://doi.org/10.1007/s11027-023-10055-8>
- Xu, W., Y. Cheng, M. Luo, X. Mai, W. Wang, W. Zhang, and Y. Wang. 2025. Progress and limitations in forest carbon stock estimation using remote sensing technologies: A comprehensive review. *Forests* 16 (3): 449. <https://doi.org/10.3390/f16030449>.
- Yu, R., Z. Zhu, and D. Zhang. 2026. Dynamic ex-post baselines for enhancing the credibility of improved forest management carbon offsets. *Environmental Science & Technology* 60 (9): 6885–6898. <https://doi.org/10.1021/acs.est.5c11387>.
- Zeng, Y., A. Lamba, H. Chen Teo, and L. Pin Koh. 2026. Limitations of carbon markets for biodiversity conservation. *Nature Reviews Biodiversity*. <https://doi.org/10.1038/s44358-026-00150-4>.

Authors and Affiliations

Chad C. Papa¹  · Melissa Kreye²  · Evan Beresford¹ · Sarah Widderich² · William R. L. Anderegg³ · Ethan P. Belair⁴ · Stephanie Chizmar⁵  · Tamara Cushing⁶  · Adam Daigneault⁷  · Margarita M. Fernández²  · Christopher S. Galik⁸ · Jason Gibson⁹ · John S. Gunn⁴  · Barbara Haya¹⁰ · Daniel J. Hayes⁷  · Matthew D. Hurteau¹¹  · Lilli Kaarakka¹²  · Tammy Kowalczyk¹³  · Gregory Latta¹⁴  · David M. McEvoy¹⁵  · Kimberly A. Novick¹⁶  · Raju Pokharel¹  · Tatyana Ruseva¹⁷  · Brent Sohngen¹⁸ · Jake Stanton¹⁹ 

✉ Chad C. Papa
papachad@msu.edu

- ¹ Department of Forestry, Michigan State University, East Lansing, MI, USA
- ² Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA, USA
- ³ School of Biological Sciences, University of Utah, Salt Lake City, UT, USA
- ⁴ The Nature Conservancy, Arlington, VA, USA
- ⁵ U.S. Department of Agriculture, Forest Service, Southern Research Station, Durham, NC, USA
- ⁶ School of Forest, Fisheries, and Geomatics Sciences, University of Florida, Gainesville, FL, USA
- ⁷ School of Forest Resources, University of Maine, Orono, ME, USA
- ⁸ Department of Public Administration, North Carolina State University, Raleigh, NC, USA
- ⁹ The Weyerhaeuser Company, Seattle, WA, USA
- ¹⁰ Goldman School of Public Policy, University of California Berkeley, Berkeley, CA, USA
- ¹¹ Department of Biology, University of New Mexico, Albuquerque, NM, USA
- ¹² Department of Natural Resources Management & Environmental Science, California Polytechnic State University, San Luis Obispo, San Luis Obispo, CA, USA
- ¹³ Department of Accounting, Appalachian State University, Boone, NC, USA
- ¹⁴ Department of Natural Resources and Society, University of Idaho, Moscow, ID, USA
- ¹⁵ Department of Economics, Appalachian State University, Boone, NC, USA
- ¹⁶ School of Public and Environmental Affairs, Indiana University Bloomington, Bloomington, IN, USA
- ¹⁷ Department of Government and Justice Studies, Appalachian State University, Boone, NC, USA
- ¹⁸ Department of Agricultural, Environmental, and Development Economics, Ohio State University, Columbus, OH, USA
- ¹⁹ Indian Land Tenure Foundation, Little Canada, MN, USA