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ORIGINAL PAPER

Prioritizing Opportunities to Empower Forest Carbon Decisions Through Strategic Investment in Forest Modeling Capacity

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Abstract
Forest ecosystems play a crucial role in the global carbon cycle, acting as substantial carbon sinks and offering pathways for climate change mitigation and adaptation strategies, including greenhouse gas (GHG) emission offsetting and bioeconomic opportunities collectively referred to as Natural Climate Solutions (NCS). Over 100 forest carbon modeling experts, primarily from the US, were engaged through a Forest Carbon Modeling Group (FCMG) to identify and prioritize research needs, opportunities, and knowledge gaps for refining the application of NCS to meet a growing spectrum of GHG mitigation and adaptation strategies initially focused on US forests with possible applicability to other temperate/boreal systems. This engagement informed the development of a framework for forest carbon decision-making, which offers a scalable, hierarchical, and transdisciplinary approach that can address immediate research needs (e.g., regeneration modeling) while advancing critical, long-term scientific advances (e.g., lateral flux modeling) that aligns technology and model development with perspectives across users and sectors.

Keywords Forest carbon · Natural climate solutions · Modeling · Biometrics

Introduction

Forests play a pivotal role in the global carbon cycle, serving as vast reservoirs that store and sequester atmospheric carbon dioxide (CO_2) that can also directly mitigate the effects of climate change (Fahey et al. 2010; Ameray et al. 2021; Pan et al. 2024).

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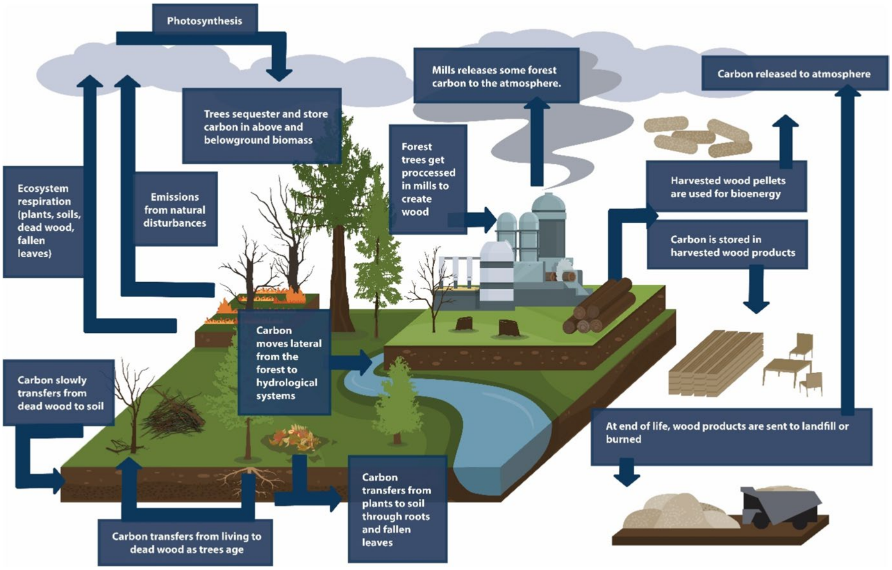

Fig. 1 Conceptual diagram of forest ecosystem carbon flux dynamics, illustrating the cyclical movement of carbon among various pools and processes. Carbon pools include aboveground (e.g., trees, some of which are transferred to persistent harvested wood products or more transient wood pellets for bioenergy) and belowground biomass (e.g., fine and coarse roots), deadwood, litter, and soil organic carbon. The directional arrows between these pools depict the fluxes of carbon, encompassing processes like photosynthesis that fix carbon dioxide from the atmosphere, respiration from plants and soil organisms that release carbon back into the atmosphere, decomposition of organic matter (e.g., heterotrophic respiration via fungi) that recycles carbon within the system, and disturbances, such as fire or harvesting, that can cause a release or redistribution of carbon. Quantifying this flow of carbon is crucial for understanding forest contributions to and interactions with the broader global carbon cycle

These complex ecosystems represent the largest net terrestrial carbon sink globally (Domke et al. 2020; Pan et al. 2024). Where forest carbon is transferred to harvested wood products (HWP), they also offer a potentially durable form of carbon storage outside forest system boundaries (Fig. 1) (Allen et al. 2022; Murray et al. 2024), often extending carbon residence time for decades while potentially displacing more greenhouse gas (GHG)-intensive products (e.g., concrete and steel) and energy sources (e.g., coal) (Gustavsson et al. 2006, 2017; Woodbury et al. 2007).

The biodiversity and ecosystem services forests offer are equally vital to society providing buffering and adaptation opportunities for communities facing broader global change threats such as land degradation and extreme weather events (Bhattacharjee and Behera 2018; Guido et al. 2023).

Recognizing this, forest-based Natural Climate Solutions (NCS) (Ellis et al. 2024) are increasingly featured in climate change strategies (Giebink et al. 2022) adopted across geographic scales (Pett-Ridge et al. 2023; Marvin et al. 2023) to lower GHG concentrations and provide co-benefits to society (e.g., insetting) (World Economic Forum 2022). In the US and beyond, a range of national legislation and policy developments have increased funding and institutional support for public and private sector entities to ensure land sector carbon resilience, while also maintaining other ecosystem services (Ellis et al. 2024; European Union 2024) (e.g., Inflation Reduction Act HR-812–118; see The White House 2023). Carbon resilience can be defined as the capacity of forests to maintain net carbon sequestration over relatively long-time spans, especially within the context of increasing disturbance intensity and climate change. Beyond the forest system boundaries, such resilience may be coupled with the GHG displacement opportunities of long-lived HWP to maintain or increase carbon storage. Of important note, the strength of the forest carbon sink may be at increasing risk of loss (Domke et al. 2023), especially in temperate and boreal zones where climate change and related disturbances are driving large-scale emission events (Nabuurs et al. 2013; Hlásny et al. 2021; Patacca et al. 2023; Zheng et al. 2023; Pan et al. 2024). The anticipated role of forests in climate mitigation and adaptation strategies may necessitate a more rigorous decision support approach that focuses on developing and distributing the most accurate and precise forest carbon information (i.e., Measurement, Monitoring, Reporting, and Verification [MMRV] standards, The White House 2023) with low latency to inform the largest future array of potential project-scale applications and national policies.

Current approaches to model forest carbon, particularly the dynamic cycling of carbon through forest ecosystems and lateral transfers across forest system boundaries (Murray et al. 2024), are rooted in foundational ecological principles (Odum 1969) with a history of informing forest planning. The increasing focus on forest-based NCS has rapidly expanded this field to international prominence, now influencing global trade discussions, financial markets, and policy, ultimately playing a key role in our planet's future climate (The White House 2023). Despite the need to improve forest carbon information, decades-old accounting system boundaries, models, and scientific standards persist as governing paradigms (e.g., land use classes) (IPCC 2006; European Union 2023a; Thornton et al. 2023). For example, various tree dynamics (e.g., Forest Vegetation Simulator [FVS]; Crookston and Dixon 2005), forest management, and carbon modeling systems (European EFISCEN; Nabuurs et al. 2002) in addition to forest carbon accounting frameworks (e.g., Canadian Carbon Budget Model [CBM]; Kurz et al. 1995) were created decades ago for a variety of applications, such as forecasting project-scale merchantable timber yield or estimating national level carbon budgets (Ellis et al. 2024). While such status quo approaches are familiar, relatively widely used, and have the advantage of being relatively straightforward to implement, they rely on tools and associated data inputs that were not necessarily designed for quantifying carbon cycle dynamics at the spatial and temporal resolutions necessary for rapid and robust evaluation of forest NCS opportunities (Ellis et al. 2024). Furthermore, they were not necessarily designed to offer the rigorous spatial scaling needed to inform policy development (The White House 2023) or offer transparent accounting and appropriate communication of uncertainty to inform program investments (Larocque et al. 2008).

While the science to support these efforts has been advancing (Novick et al. 2022b), charting a path towards a more rigorous decision-support approach reveals limitations in current approaches and the complexities of accurately representing drivers of change in carbon storage and sequestration within and beyond the forest ecosystem. Forests are deeply complex systems, with diverse plant associations and stand structures across biophysical gradients, disturbance histories, and management intensities (Ayres et al. 2014; Xu et al. 2022), further complicated by our emerging understanding of belowground communities and soil organic carbon (Lehtonen and Heikkinen 2016; Prescott 2023). This diversity makes modeling forest carbon dynamics and the potential benefits and unintended negative effects of forest NCS highly complex (Nabuurs et al. 2023; Pett-Ridge et al. 2023). Compounding these complexities are the variable impacts of global change factors and associated feedback (e.g., climate change, insects, disease, invasive species) that affect tree growth and survival (Domke et al. 2023; Schelhaas et al 2018) as well as biodiversity and food production (The White House 2023; Nabuurs et al. 2023).

Beyond the forest ecosystem, product processing and transporting efficiencies coupled with product end uses and disposal practices further complicate efforts to quantify the total carbon transferred from the forest to HWP and life cycle assessments of their total carbon footprint (Li et al. 2022; Zhao et al. 2022) (Fig. 1). These sources of uncertainty, from statistical (e.g., model inputs), scenario (e.g., markets and pricing), to deep uncertainty (e.g., climate change impacts) (Walker et al. 2003; Radke et al. 2017; de Pellegrin Llorente et al. 2023), complicate the comprehensive assessment of NCS practice adoption from parcels to jurisdictions (The White House 2023; Nabuurs et al. 2023). However, accurate and precise estimates across space and time are crucial for assessing forest attributes and dynamics associated with the carbon cycle across all scales (Hayes et al. 2023), from the forest carbon budgets of discrete projects to international climate change agreements. Recent monitoring data and socioeconomic sciences advances may offer emerging opportunities to refine forest carbon decision support. Advancements in data analytics (e.g., artificial intelligence [AI] and mechanistic model improvements) and infrastructures (e.g., cloud computing), coupled with improved remote sensing approaches (e.g., LiDAR, synthetic aperture radar [SAR], and multispectral satellite imaging) may offer an opportunity to improve our ability to measure and understand forest carbon dynamics across scales with reduced uncertainties (Wulder et al. 2012; Kaasalainen et al. 2015; Novick et al. 2022b). Collectively, improved forest carbon modeling may not only help determine which emerging analytical opportunities are of utility but also elucidate tradeoffs and opportunities between offsetting versus insetting paradigms (World Economic Forum 2022) as the climate benefits sought by ongoing and past policies are revisited (Allen et al. 2022; Cullenward et al. 2023).

The overall goal of this study is to outline general guidance for developing a comprehensive, sector-relevant forest NCS decision support systems based on facilitated engagement with forest sector scientists, experts, and power users in an emergent forest carbon modeling consortium (Forest Carbon Modeling Group [FCMG]). Developed through a partnership agreement (USDA 22-JV-11242305–083) between the USDA Forest Service (Forest Service) and the National Council for Air and Stream Improvement, Inc. (NCASI), the FCMG engaged over 100 leading experts in forest carbon modeling to explore: 1) the evolution of forest carbon modeling within the ambition of international agreements, domestic policies, and emergent third-party voluntary markets to provide historical context and present challenges; 2) the pivotal role of forest biometrics and modeling in terrestrial ecosystem assessments, underscoring the necessity for a multidisciplinary framework; and 3) the compendium of decision support tool specifications for forest carbon science to meet diverse requirements of planning and implementation across scales and economic sectors. This paper presents initial findings from this engagement, including a list of important forest carbon resource questions agreed to by a consensus of participants, rated technical advances, and the expanded discussion among participants.

Methods

In 2023, the FCMG gathered over 100 experts from academia (n = 29), government (n = 30), industry (n = 36), and non-profit organizations (n = 8) primarily from the US but with additional participation from Canada and Europe (Supplemental Table 1) through a series of four virtual engagements, followed by several breakout sessions during June and July 2023 to focus on specific topic areas. Participants were selected based on their expertise, research focus, and/or actively working in roles directly related to carbon modeling, research, or policy. The selection process aimed to include diverse professionals from across sectors to ensure comprehensive input. Membership, while selective, remained open to all individuals who expressed interest in contributing to the collaborative effort. Perspectives from the group provide opportunities for FGMG's findings to be relevant across portions of the northern hemisphere temperate/boreal forest ecosystem, given resource and socioeconomic similarities (for example see Box 1). The creation of the FCMG was meant as an initial engagement with expectations that attendance would grow as this study and journal communication were created with expectations that a co-benefit would be the expanded inclusivity.

Box 1. Temperate and Boreal Forest Carbon Modeling – European Perspective

Encompassing more than a third of the continent's total land area, European forests serve as an invaluable resource, consistently providing a multitude of products and services (Schelhaas et al. 2018). The forest area and growing stock have demonstrated a steady increase since the 1950s (Gold et al. 2006; Fuchs et al. 2015). However, in recent years, the escalating impact of climate change has led to more severe and frequent disturbances in European forests (Patacca et al. 2023), accompanied by early indications of carbon saturation (Nabuurs et al. 2013). The European Union (EU) Commission has acknowledged these information needs by pursuing the establishment of an EU-wide Forest Monitoring Law with such data potentially leveraged during scaling exercises to project various scenarios into the future, enabling a comprehensive assessment of their impact on the expansive forest landscape across the continent. Forest modeling in Europe has undergone active development over the past few decades (Pretzsch et al. 2008). Presently, various initiatives are underway to integrate data on a European scale and establish standardized methodologies for forest modeling such as high-resolution forest resource growth modeling and land-use models (Valin et al. 2013; Schelhaas et al. 2022). Similar to technical challenges and approaches across North American forests, spatially explicit National Forest Inventory plots are the basis for projecting future forest growth under user-defined scenarios. In contrast, there are modeling approaches that use aggregated data, downscaled to the grid level, to model changes in land use and associated GHG emissions. A persistent challenge lies in the development of dynamic modules for harvesting, natural mortality, and ingrowth. These modules need to be not only individually sensitive to climate change but also responsive to changes in stand conditions influenced by the other modules (Schelhaas et al. 2022). On the other hand, use of aggregated data faces a distinct challenge related to handling uncertainties associated with parameters intrinsic to the model, such as behavioral parameters, emission factors, and future technologies (Valin et al. 2013). Not only are these challenges critical to refining the accuracy and reliability forest growth and land-use change projections but Europe also faces challenges to accessing ground-based data, thorough coupling with remote sensing data, links to multi-sectoral modelling, use of new techniques such as AI, and linkages to economic and market modelling

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The facilitated engagements and subsequent synthesis were centered on a series of primary questions posed to participants: 1) how do we contextualize the role of forest carbon modeling within the broader scope of ecosystem monitoring and modeling; 2) what are the critical knowledge and model gaps; and 3) how can NCS-associated forest biometrics and modeling be integrated and prioritized with a diverse set of ecosystem models and data streams? Drawing on participant feedback, knowledge gaps were identified that could serve as a foundation for rating priority areas for improvement.

Following the virtual engagements, the FCMG was surveyed to understand the challenges and opportunities in forest carbon modeling. Participants were asked to rate knowledge gaps on a scale from one (not a priority) to five (high priority). This rating was based on the perceived importance of each topic to the participant's individual work and organizational goals. Survey distribution was accompanied by email notifications explaining the exercise's purpose, the expected time commitment, and the importance of their participation in guiding future research and development in forest carbon modeling. Reminders were also sent to encourage survey completion, ensuring a high response rate. While all participants identified forest carbon modeling topic areas, 58 participated in the priority rating exercise (academia [n = 18], government [n = 10], industry [n = 23], and non-profit organizations [n = 7]). Industry participants that responded to the priority rating exercise were categorized into four broad groups: forest landowners (n = 13), manufacturers (n = 1), integrated organizations that are landowners and manufacturers (n = 1), and service providers or consultants (n = 8). It should be noted that the initial FCMG focus was US centric, with the inclusion of Canadian and European participants expanding throughout the study period and the expansion to other domains expected post-study. In addition to the survey, participants developed consensus resource-related questions and a schematic of future model development workflow via facilitated dialogues to assist with designing the architecture (e.g., data governance, model verification, and uncertainty communication) for refining and distributing forest carbon modeling advances.

Results

FCMG participants broadly identified six topic areas regarding forest carbon decision support needs: i) conservation and management implications, ii) quantification and incentivization of resilience, iii) definitions and standards, iv) alignment with national and global objectives, v) error analysis and model refinement, and vi) market paradigms and governance (Fig. 2, Supplemental Table 2). As a component of each topic area, hypothetical questions regarding information needs were postulated to inform modeling and decision-support refinements (Table 1).

Regarding the exploration of more explicit modeling needs, participants across sectors had varying perceptions of the importance of forest carbon modeling needs and gaps (Fig. 2, Supplemental Table 2). All sectors strongly prioritized topics related to improving consistency and standardization in forest carbon quantification and uncertainty reporting. Respondents across sectors emphasized the need to build a future workforce skilled in data literacy, computer coding, mathematics, and ecology. However, respondents from the forest industry sector rated this less highly than others. Most sectors considered belowground carbon modeling and integration of disturbance into forest carbon models to be of high priority, with some variations in overall importance. For example, government respondents indicated incorporating natural disturbances, such as wildfire or extreme events, was a higher priority than respondents from other sectors. Moderately rated topics included more clearly documenting the variety of forest carbon-related applications and developing more cost-effective monitoring techniques aligned with such applications. Incorporating genetics into projection models or investigating how different ownership types affect modeling approaches were generally not considered immediate priorities in the field, except for industry sector participants who rated it high. The variation in the importance attached to these topics by different sectors highlights the need for greater collaboration and dialogue across sectors and geographies inclusive of communities not included in this initial engagement.

Although no modeling approaches or systems (whether stochastic or process-based) were excluded from discussions, participants expressed interest in focusing on the FVS as an example decision support tool, highlighting areas for improvement which varied across sectors (Fig. 3, Supplemental Table 2).

There was strong consensus across sectors on the need for models that better address management across diverse forest types and ownerships, reflecting diverse stewardship practices. A “strengths, weaknesses, opportunities, and threats analysis” (SWOT) for FVS highlighted respondents’ desire for the development of robust

Table 1 Example forest carbon resource questions by topic area developed by Forest Carbon Modeling Group (FCMG) engagements that future decision support systems may need to objectively inform

Topic	Hypothetical questions regarding information needs
Conservation and Management Implications:	• Does preserving old-growth forests also preserve forest carbon stocks? • What is the correct baseline year to adopt for monitoring effects of forest carbon management policies? • What is the appropriate balance between preserving current forest carbon stocks and preventing future emissions? • Where is the most impactful focus of management efforts: on forest plantations for long-lived wood products with high-GHG product displacement, or on protecting carbon-dense but potentially relic forests that are subject to long-term disturbance regimes? • Where and when can forest managers meaningfully reduce the permanence risks of forest carbon and increase the durability of associated projects?
Quantification and Incentivization of Resilience:	• How do we quantify and incentivize forest carbon resilience? • How do we estimate the optimal carbon density in a landscape while balancing other ecosystem services such as water and biodiversity, and the potential for climate adaptation? • What socio-economic factors determine landowner willingness to adopt and sustain management practices that enhance carbon resilience?
Definitions and Standards:	• How is 'forest' defined across the land use spectrum, and what implications does this have for carbon estimation in urban and agroforestry contexts? • What is the role of forest carbon removals in offsetting fossil fuel emissions? What is the definition of insetting in this context?
Alignment with National and Global Objectives:	• How do we align carbon insetting (i.e., businesses reduce emissions within their own operations and value chain) practices with offsetting paradigms in national policies and encourage uptake via reduced uncertainties at project scales? • How do we connect various forest carbon modeling techniques and system boundaries to enhance decision-making across scales? • How to scale up forest carbon project measurement, monitoring, reporting, and verification to align with Nationally Determined Contributions?
Error Analysis and Model Refinement:	• What is the error structure (i.e., attribution of total error to sources) in forest carbon and albedo estimates? • How can we identify and prioritize sources of errors for effective data and modeling improvements? • What is the optimal use of emerging AI technologies when building these forest carbon knowledge systems? • How can we anticipate future data gathering techniques (i.e., autonomous drones) to optimize future modeling systems? • How can lateral transfer models be incorporated into market and management decisions support applications? • How to reconcile top-down (e.g., satellite-based GHG detection) and bottom-up (e.g., stand-level estimation) models and monitoring?

Table 1 (continued)

Topic	Hypothetical questions regarding information needs
Market Paradigms and Governance:	• How can system boundaries be analyzed to develop more effective market paradigms and governance structures? • How can we enhance the likelihood of durable forest-sector removals over time and space? • How do we objectively evaluate cost efficiencies and evaluate market models? • How is successful NCS objectively defined?

uncertainty propagation techniques and streamlined capabilities for assessing model sensitivity to changes in independent variables (e.g. site productivity). Incorporating more complex silvicultural practices into FVS was rated the lowest, particularly by government and non-profit participants. These insights collectively point to the necessity of enhancing FVS to align with the evolving needs of forest carbon modeling and management along with emerging data streams such as LiDAR-derived data that augments traditional tree/plot-level records. Finally, FCMG participants collectively developed a schematic (Fig. 4) illustrating the modeling and data components of a forest carbon decision support system that explicitly addresses the aspects of forest ecosystem carbon attributes and interactions (via transfers) with socioeconomic and non-forest systems (Fig. 1).

Discussion

The results of this study, coupled with the participation and technical contributions of over 100 experts reinforce the premise that forest biometrics occupies a central and interdependent role in the complex endeavor of ecosystem modeling and monitoring for NCS assessments, particularly for carbon offsets, MMRV, and policy. Forest biometrics largely focuses on tree- and stand-level variables such as tree growth, mortality, and forest composition (Crookston and Dixon 2005) and acts as a foundational layer for a range of related scientific disciplines, such as climate modeling, albedo calculations, life cycle analyses, natural disturbance modeling, silvicultural practices, lateral transfer mechanisms, and forest product markets (Fig. 1) (Burkhart and Tomé 2012; Daigneault et al. 2022; Novick et al. 2022a, 2022b). For example, estimates from forest biometrics feed into climate models to more accurately predict broader climatic effects beyond atmospheric carbon concentrations, such as albedo variations (Latif 2010) and evapotranspiration (Wang et al. 2021). The role of lateral transfers is better understood when biometrics data are combined with insights from natural disturbance ecology, silviculture, and soil science (Johnsen et al. 2005; Woodall et al. 2015). Silvicultural science connects with biometrics to drive model refinement to reflect management practices better and inform sustainable forest management strategies that are both ecologically sound and economically viable (Valipour et al. 2021). Yet, while forest biometrics and modeling may be critical components for rigorous and transparent evaluation of NCS practices, their potential may only be fully realized when interwoven with other scientific and socioeconomic disciplines.

For example, refined modeling of various HWP mixes aligned with altered silvicultural systems in planted forest stands can refine our understanding of how social and financial levers, such as market-driven and governmental incentives, interact to influence climate change trajectories (McGinley et al. 2023). Wildfire modeling integration adds another dynamic component, allowing us to anticipate and manage wildfire consequences and estimate the contributions of fire-adapted ecosystems to global carbon cycles (Conard and Solomon 2008; Loehman et al. 2014; Parsons et al. 2017; Allen et al. 2023). Theories from ecosystem ecology are necessary to understand how carbon is redistributed throughout the entire forest and the extent to which changes in tree biomass are coordinated with the net ecosystem carbon sink (Novick et al. 2022a).

The prevailing architecture of forest carbon modeling systems across North America and the northern hemisphere (Box 1) reflects the original scope and reporting structures for which they were created (i.e., IPCC 2006). Decades ago (Newell et al. 2014), the United Nations Framework Convention on Climate Change (UNFCCC) developed consensus technical approaches for monitoring forest carbon (IPCC 2006). These approaches, including a net-zero accounting paradigm to estimate annual gross emissions and removals of CO_2 from the atmosphere across land-sector and emission scenarios (IPCC 2006), contributed to shaping the mechanisms we use today (e.g., Global Stocktake, UNFCCC 2023). Similarly, domestic monitoring

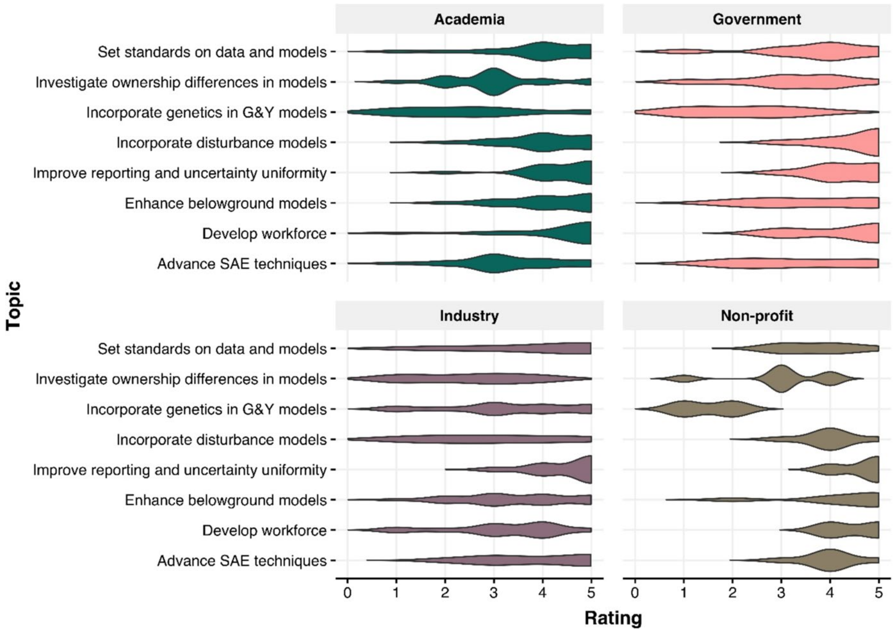

Fig. 2 The proportion of responses by priority ratings (0 = low priority, 5 = highest priority) among forest carbon modeling topic areas by sector (e.g., academia or government) derived from Forest Carbon Modeling Group (FCMG) facilitated engagements. Acronyms: SAE (Small Area Estimation), G&Y (Growth and Yield)

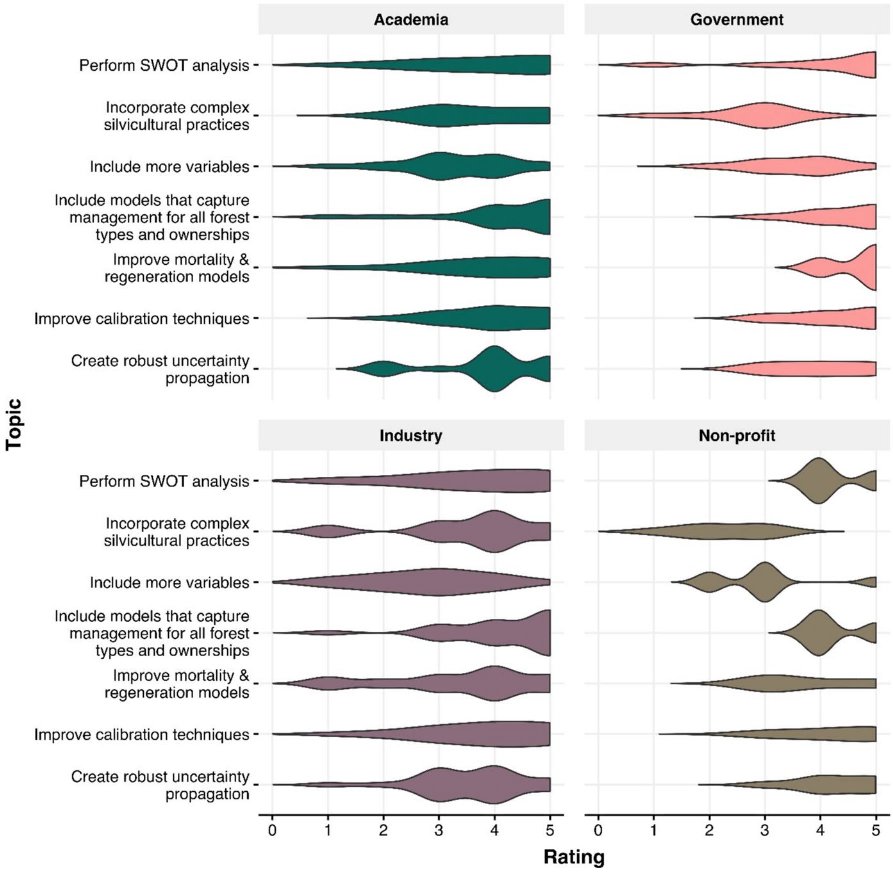

Fig. 3 The proportion of responses by priority ratings (0 = low priority, 5 = highest priority) among Forest Vegetation Simulator (FVS) topic areas by sector (e.g., academia or government) derived from Forest Carbon Modeling Group (FCMG) facilitated engagements. Acronyms: SWOT (Strengths, Weaknesses, Opportunities, and Threats analysis)

policies and mechanisms focus on estimating emissions and removals of fossil fuel and land sector carbon fluxes at the jurisdictional scale (Daigneault et al. 2022) and often seek to reconcile bottom-up and top-down monitoring approaches (The White House 2023). At even smaller spatial scales, carbon markets have emerged with explicit protocols to allocate financial capital to projects where avoided emissions or additional carbon removals could be reasonably attained over defined periods while avoiding leakage (Calel 2013; Newell et al. 2014). Whether the goal is to meet UNFCCC commitments, develop state-level net zero targets, or estimate risks of reversal associated with an individual carbon project (Deconinck et al. 2023), intrinsically across all these accounting paradigms, projecting forest carbon attributes in the face of an uncertain future (i.e., social and environmental change) is paramount.

More recently, the failure to achieve globally meaningful reductions in the rate of atmospheric CO_2 accrual (NOAA 2023) may have elevated the expansion of

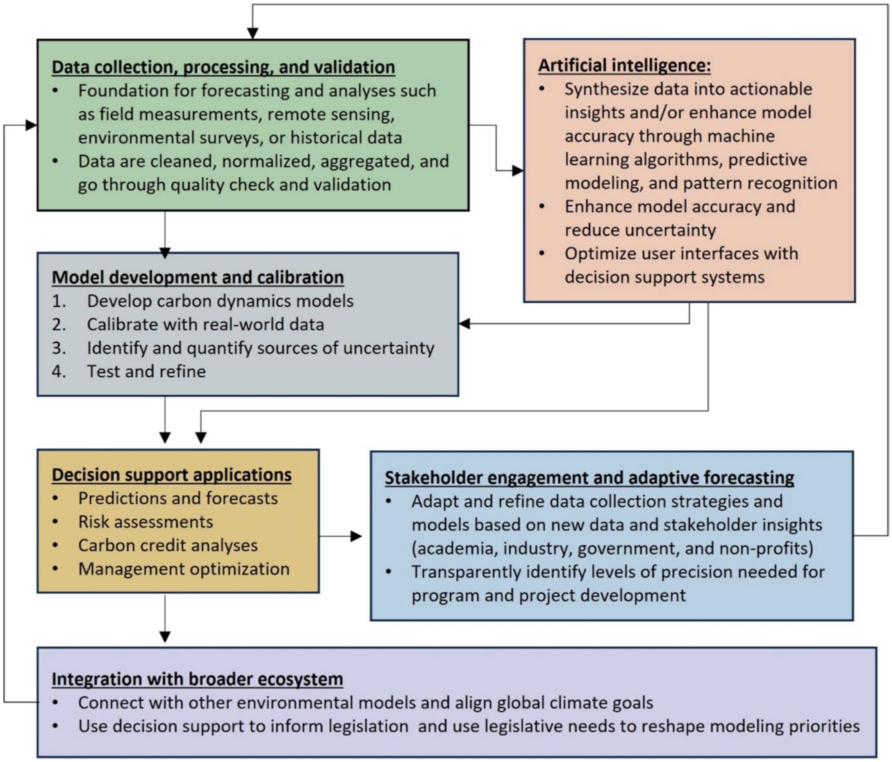

Fig. 4 Integrated Framework for Forest Carbon Decision-Making: This flowchart delineates the interconnectivity of data collection, artificial intelligence, policy development, user engagement, and adaptive management in informing natural climate solutions (NCS). It emphasizes a system where each component is interdependent, facilitating a robust exchange of information and feedback. The central focus on forest biometrics and modeling ensures that each element—ranging from raw data acquisition to legislative action—contributes to and benefits from the precision and predictive power of the models. This comprehensive structure is designed to be agile, accommodating new scientific insights and technological advancements, while remaining grounded in practical application for climate mitigation and adaptation strategies

forest carbon monitoring sciences, associated data streams, and concomitant policies across jurisdictional scales (e.g., insetting, World Economic Forum 2022). Emergent international and national policies centered on forest resources and carbon policies, such as the European Union Deforestation Regulation (EUDR; European Union 2023a), the EU Carbon Farming Regulation (European Union 2023b), UNFCCC Global Stocktake (UNFCCC 2023), US Mature and Old-Growth (Pelz et al. 2023), Inflation Reduction Act (IRA) programs, and the US MMRV strategies (The White House 2023) have highlighted the need to better integrate forest carbon cycle and modeling sciences into policy frameworks. Further, increasing societal scrutiny around the efficacy of forest carbon project offsets (i.e., overstatement of benefits (Pears et al. 2023)) has been met with accelerating focus on increasing confidence in the value of offsets (Badgley et al. 2022a, 2022b; Haya et al. 2023) and what additional paradigms such as insetting (World Economic Forum 2022) may offer. Such contemporary social and economic developments reveal a range of pressing information needs regarding forest carbon dynamics, which might be considered in developing future forest carbon estimation and projection systems to answer such questions (Table 1).

As the field of forest biometrics in service to NCS and carbon monitoring has evolved, there has been an emerging consensus identified by this study and others (de Pellegrin Llorente et al. 2023) on needing a more universally applicable modeling system that meets the decision-support and MMRV needs of diverse ownerships and sectors. FVS might be considered one such current software system that could be built upon following emerging guidance from this study and the FCMG. In planning the architecture of future forest decision support systems such as a potentially refined FVS, it is essential to orient design specifications with the needs and insights of those directly engaged in forest management and policy development, not to mention those individuals living across these landscapes (i.e., science co-production (Nagel et al. 2017)). User and developer engagement is paramount to enable refined models and applications to effectively serve their intended purpose (Petr et al. 2014). The FCMG engagement highlighted key design specifications to answer key resource questions (Table 1) that future applications may seek to integrate to serve the existing and emerging needs of policymakers, the forest product sector, and carbon markets. These specifications describe a forest decision support system that is scalable (e.g., stands to jurisdictions), adaptable (e.g., reacts to emerging policies), hierarchical (e.g., stand projections within landscape-scale fire propagation models), and transdisciplinary (e.g., albedo and old-growth estimation).

The range of applications for models that meet such design aspirations might be broad, requiring accommodation of diverse spatial and temporal scales to foster transparency and consistency across a broad set of potential end uses. For example, accommodating various management and biomass utilization options across sectors and accounting paradigms, such as enabling voluntary carbon credit markets to appropriately scale domestically traded removal estimates towards national obligations under the UNFCCC, necessitates scalability. Spatial scales must be adaptable, ranging from granular, stand-level data to comprehensive national summaries. Temporally, models may reconcile user needs to understand historical data and trends while projecting scenarios and associated uncertainties several decades into the future.

Forest carbon decision support systems also may need to be dynamic and adaptable to incoming information on changing social and environmental characteristics to match the rate of change across all these systems that are responding to global change factors (i.e., economic trade and wildfires) (Fig. 3) while seeking to reduce uncertainty (Yousefpour et al. 2014; Pukkala et al. 2021). In the age of big data and near real-time data collection, hierarchical approaches that leverage a wide range of data streams could fill spatial and temporal gaps in carbon flux estimates that historically have only relied on biometric measurements (i.e., integration of high-frequency satellite data, flux towers across spatial and temporal domains, tree ring networks; see Hemes et al. (2021); Novick et al. (2022a); Novick et al. (2022b)). Another opportunity to consider is the latency of data refresh rates, including options for both real-time updates and annual summaries while optimizing the alignment between the relatively high latency of in-situ plot networks (e.g., soil carbon sampling) versus the low latency of flux towers and remotely sensed information. Accelerated and expanded access to ground-based country-level forest inventory data is still unavailable even within the EU, which is a modeling necessity (Nabuurs et al. 2023; see Box 1. Building dynamic and scientifically robust carbon modeling applications may require transparent processes within cyberinfrastructure to integrate advancements in data and models while enabling coherent monitoring over time.

Future forest carbon decision support systems may also need to be dynamic and adaptable to evolving science and technology across fields (i.e., transdisciplinary, Fig. 4), for example, moving towards conversational interfaces (i.e., large language models and/or retrieval-augmented generation (See Floridi and Chiriatti 2020; Gao et al. 2023)) to enhance application accessibility and continuously improve accuracy. Applications may leverage data-hungry and computationally expensive algorithms (e.g., deep learning (Hamedianfar et al. 2022)) or deep reinforcement learning (Lapeyrolerie et al. 2022)), which necessitates transparency (e.g., not only rapid availability of data and code, but also reporting of new algorithms pitfalls (Bayram et al. 2022; Chapman et al. 2023)). Applications may operate across social (e.g., preservation to conservation), economic (e.g., market elasticity, prices), and environmental spectrums (e.g., rates of expected climate change), and likely be transdisciplinary (e.g., silvics and building architecture) in scope to generate decision support (Fig. 4). Such applications can serve as a primary means for delivering forest carbon modeling advancements to users while addressing the highest-rated priority within the FCMG survey: enhance uniformity in carbon flux reporting and uncertainty quantification. Most importantly, accuracy and uncertainty across all sources (e.g., measurement, modeling, and/or sampling) should be considered and transparently presented for a greater understanding of the key drivers of carbon change while instilling confidence in management and policy decisions aimed at climate stability among the many forest sector co-benefits inclusive of communities and economies. This study potentially points to future endeavors where contemporary frameworks and associated limitations of net-zero targets at various jurisdictional scales could be viewed as an independent model among a variety of alternatives (e.g., insetting approaches along international supply chains, World Economic Forum 2022) leading to greater policy efficacy and reduction of model selection error (Melson et al. 2011). Consideration of alternative paradigms and models beyond net-zero (Allen et al. 2022), might result in more substantial ecosystem and net-climate benefits (i.e., climate stability (Cullenward et al. 2023)) with concomitant reductions in uncertainty. However, the full extent of these benefits may only be discernible through deploying broader and more inclusive forest modeling systems as initially explored in this study.

Conclusions

The scope of forest carbon modeling transcends the confines of isolated lines of forest research, being part of a broader knowledge system encompassing various scientific domains within a larger socioeconomic realm inclusive of integrating user feedback, as evidenced by the engagements conducted by FCMG identifying research needs in specific areas of forest carbon science and technology. As we look toward quantification of forests' role in future climates, it is important to align our technological and methodological advancements with the needs and perspectives of users across all sectors, which not only ensures cost-effective research, but also practical on-the-ground decision-making tools while informing national and multilateral policies. This alignment may be essential for fostering resilience within forest ecosystems and enhancing their role in mitigating climate change. In addition, strategic and targeted investment is likely necessary to improve and expand forest biometrics capacity in the US, given current demands and workforce trends.

Immediate steps might entail: 1) clearly defining what success looks like across users and diverse forest ecosystems; 2) enumerating associated tasks within an integrated framework along with workplans that may build upon current software systems such as FVS; 3) enhancing technical collaborations across similar biomes and associated socioeconomic factors such as northern hemisphere temperate/boreal forests; 4) review, alignment, and refinement of widely used and contemporary models or carbon accounting frameworks (e.g., CBM, FVS, LANDIS, and EFISCEN-space); 5) enhancement and curation of vital data streams inclusive of forthcoming remote sensing platforms (e.g., space-based radar); 6) leveraging opportunities presented by AI; and 7) enhancing robust scaling and uncertainty calculation across space and time. The ensuing dialogue between science and practice may refine the accuracy and precision of our models while ensuring forest carbon modeling remains a pivotal, proactive agent in addressing global climate change challenges.

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Declarations

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