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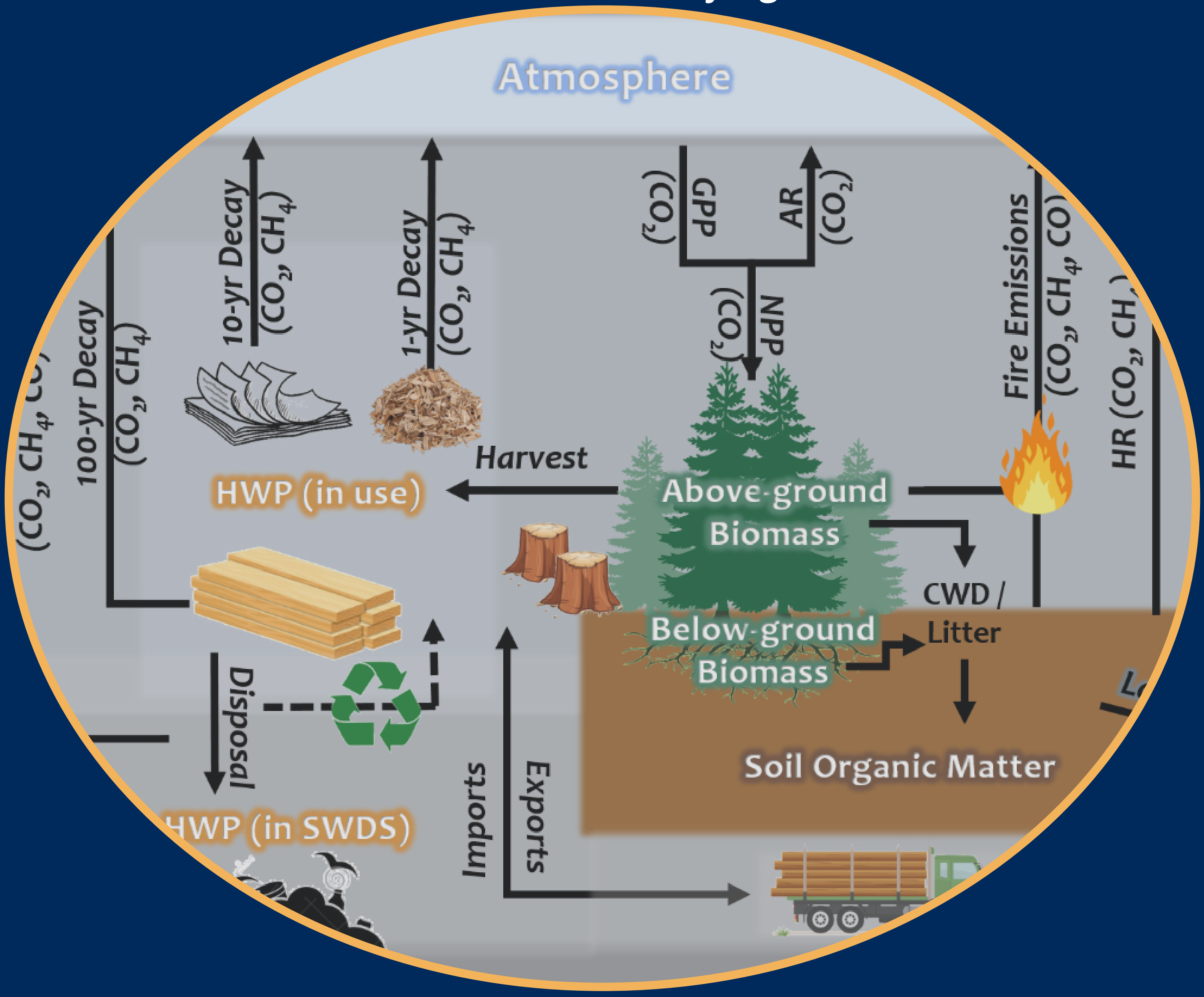
Center for Research on Sustainable Forests

Forest Carbon Accounting and Modeling Framework Alternatives

An Inventory, Assessment, and Application Guide for Eastern US State Policy Agencies



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Forest Carbon Accounting and Modeling Framework Alternatives: An Inventory, Assessment, and Application Guide for Eastern US State Policy Agencies

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Final Report

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OVERVIEW

This report provides a synthesis of information for assisting states with building capacity to engage in forest carbon inventory, monitoring, and modeling for projecting carbon outcomes of policies that support mitigation-focused forest management scenarios. Specifically, we provide:

(1) *A qualitative analysis and summary of forest carbon modeling* that describes how models work and explains the differences between various model types, including advantages and caveats in their use for a range of applications across scales in time, space, and information content.
(2) *A carbon modeling decision support framework* that can be used as a resource for assisting states in determining which forest carbon model may be best suited for both their information needs and their capacity, either within their agency staff or by way of funding necessary for contractor support.

This report discusses the practice and benefits of forest carbon modeling and is intended for a broad audience. It focuses on model types and specific tools that address the impact of forest processes and their management on carbon stocks and fluxes across multiple pools in response to economic, policy, and environmental conditions (i.e., stressors, shocks, or drivers). Here, we provide brief descriptions and applications of some of the key forest carbon models that are relevant in the context of the prevailing environmental conditions, ownership, and management approaches for forests of the eastern United States.

BACKGROUND

Greenhouse gas (GHG) accounting is required for developing climate mitigation policy and fulfilling the requirements of emissions reduction agreements. Natural and managed forest systems are a critical component of this accounting because they can take up and store substantial quantities of atmospheric carbon (Harris et al., 2021; Schimel et al., 2000). Carbon sequestration in the forest sector contributes to climate mitigation by offsetting some portion of the anthropogenic greenhouse gas emissions from fossil fuel combustion and land use change. Inventory data suggest that forests account for most of the global, land-based carbon sink, and that their rate of uptake has been maintained over recent decades (Pan et al., 2011). International agreements on climate change mitigation (i.e., the United Nations Framework Convention on Climate Change, or UNFCCC), forest conservation incentive programs (e.g., REDD+), and carbon trading markets (e.g., California Air Resources Board) are critically dependent on the ability to measure, monitor, report, and verify the impacts of forest management on increasing carbon stores while reducing carbon emissions from deforestation and resource extraction (Beane et al., 2008; van Kooten, 2017; Vargas et al., 2017).

Managing forests to enhance carbon sequestration as a strategy for mitigating future climate change is an important goal of resource policy at local, national, and international levels (Canadell & Raupach, 2008; Grassi et al., 2017). However, there is large uncertainty about the future sequestration potential in forests due to climate change, disturbance, and management scenarios (Millar et al., 2007; Williams et al., 2016). In particular, the global importance of natural forests for capturing additional carbon was recently determined to have been significantly underestimated (Cook-Patton et al., 2020). Indeed, estimates of forest carbon sequestration rates and trends differ significantly among regions and assessments, which suggests that important carbon budget components and their changes are not accurately measured or sufficiently represented among the different accounting and modeling approaches (Hayes et al., 2018; King et al., 2012).

Major Components of the Forest Sector Carbon Budget

For a defined geographic domain over a given period of time, the overall impact of the forest sector on the atmospheric GHG budget is determined by the imbalance between the anthropogenic and natural sources of carbon dioxide (CO_2) and methane (CH_4) versus the carbon taken up by its natural and managed ecosystems (**Figure 1**). Forests sequester carbon by taking up CO_2 from the atmosphere in plant photosynthesis and storing it in live biomass and dead organic matter both above- and below- ground. Carbon stocks and fluxes are highly dynamic in forest ecosystems, driven by solar radiation, air temperature, atmospheric chemistry, the availability of water and nutrients, and the ecological processes of disturbance and succession. Forest disturbances such as fire, insect outbreaks, and windthrow result in the transfer of carbon from live to dead pools and re-set the trajectory of CO_2 uptake and GHG emissions over forest succession. Depending on various factors (Wei et al., 2021), a portion of the land-derived carbon is transferred to the aquatic system, where it can be outgassed from water bodies, buried in sediments, or exported out of the watershed as organic or inorganic carbon in dissolved or particulate form (Butman et al., 2016). Additionally, carbon removed from the forest in harvest can be stored in wood products ranging from short-lived (e.g., pulp and paper) to longer-term (e.g., sawlogs) pools and eventually as solid waste disposal (i.e., landfills). Wood products of domestic origin can be exported outside of the domain at the same time as those grown and harvested outside the domain are imported; the balance of which determines the stock change of HWP produced versus consumed in the domain. Finally, after accounting for lateral transfers in wood product trade and losses to the aquatic system, the remainder of carbon sequestered in the forest sector (both ecosystem and product pools) represents the “offset” proportion of the total carbon emitted from fossil fuel combustion.

Forest Sector Carbon Accounting

Accounting methods for GHG reporting treat the gross emissions from anthropogenic sources separately from, but in parallel with, the net emissions from land sectors considering both their sources and sinks of carbon. For UNFCCC reporting, land-based sources and sinks impacted by management and human activity are accounted for by tracking carbon stocks and flows in the various land use, land-use change and forestry (LULUCF) categories (i.e., forest land, cropland, grassland, wetlands, settlements, and other land). The International Governmental Panel on Climate Change (IPCC) provides guidelines for the generic methodologies applicable across LULUCF categories (Eggleston et al., 2006) for national GHG inventory reports to the UNFCC. There are two fundamentally different approaches to accounting for LULUCF carbon emissions (transfers from a land-based pool to the atmosphere) and removals (transfers from the atmosphere to a land pool). The gain-loss method tracks both carbon additions to and removals from a land pool, and the net balance is the stock change estimate for that pool. Alternatively, the stock-difference method estimates the stock change of a pool by the difference in carbon stocks at two points in time. The annual carbon stock change (ΔC) for a LULUCF category, then, is calculated as the sum of changes from one year to the next across all pools in that category. The specific pools accounted for in the ΔC calculation will depend on the category, the method used, and the data available.

In the Forest Land category, carbon stocks and transfers are tracked within and among forest ecosystem and harvested wood products (HWP) pools (**Figure 1**). Forest pools include biomass both above- and below- ground, often tracked together as "live biomass", along with deadwood, litter, and soils that are typically combined as the "dead organic matter" pool. Carbon in HWP is typically tracked between pools in-use of various lifespans and in solid waste disposal sites (SWDS). The HWP contribution to Forest Land category emissions and removals depends on the data available, the definition of the system boundary, and the choice of calculation method. The stock change method (the *default approach*) estimates the HWP contribution from inventories of in-use and SWDS pools at two or more points in time within the reporting domain. This method calculates emissions from HWP used in the domain but does not include products harvested domestically that are exported outside of the domain. The *production approach* estimates carbon stock changes in the in-use and SWDS pools containing HWP of domestic origin, regardless of where the carbon is emitted. This method includes products made from domestic harvest exported and stored in uses or disposed of elsewhere but does not include HWP imported into the reporting domain. The *atmospheric flow approach* calculates the emissions and removals that occur within the boundary of the reporting domain. This method calculates emissions including from HWP pools in domestic consumption with the net balance of carbon imported minus that exported outside the domain.

Land-based GHG accounting requires establishing the domain's geographic boundary and the criteria used to define the areas of the different LULUCF categories. Forest Land category representation for UNFCCC reporting is often based on the United Nations Food and Agricultural Organization definition as an area covering at least 0.5 ha with trees greater than 5 m in height and canopy cover more than 10% (FAO 2010). This distinguishes Forest Land from other LULUCF categories that also contain trees but of lesser stature and areal coverage. However, the Forest Land definition can be complicated by the “managed land” proxy used for national GHG reporting (Grassi et al., 2021). A reporting domain will only get “credit” for carbon removals in their managed lands, but many forest areas are considered "unmanaged" because there is no evidence that direct human intervention has influenced its condition (Ogle & Kurz, 2021). Defining the land base for what is “managed forest” and thus included in GHG reporting will have implications for policy actions to mitigate GHG emissions (Grassi et al., 2017). Not accounting for the carbon fluxes in these areas can result in significant discrepancies with estimates of forest-based sources and sinks from other measurements and modeled estimates of regional carbon budgets.

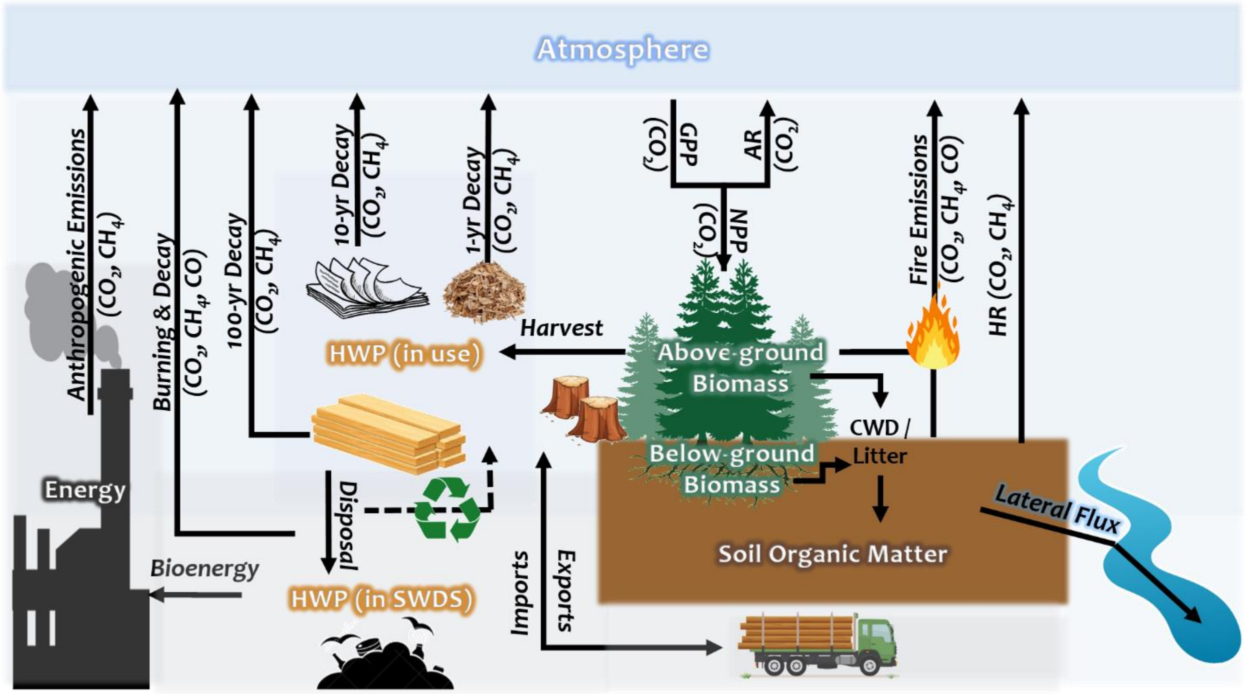

Figure 1. *Pool and flux diagram illustrating the stocks and flows among the major components of the carbon budget of the managed forest sector. The net exchange of carbon-containing greenhouse gases (GHGs: CO_2, CH_4, CO) between the atmosphere and the land surface over a regional-scale domain is estimated directly using top-down approaches such as atmospheric inversion modeling. From the bottom-up, regional-scale land-atmosphere exchange is estimated indirectly by summing across the inventory or modeling of the major GHG source and sink components - both natural and anthropogenic – in the managed forest sector. Fossil fuel emissions are inventoried and reported with relatively small uncertainty at state / province to national levels. National forest inventory (NFI) programs are typically cited as the best available information on carbon stocks and stock changes across the managed forest sector. As a key part of these inventories in forests, GHG emissions from wildfire are estimated based on aerial survey and satellite remote sensing of burned areas combined with models of fuel loads and fire behavior. While NFIs provide reliable estimates of the change in tree biomass and harvested wood*

products pools between two points in time from the periodic measurement of the plot networks, other pools - especially soils - are more uncertain. Other, research-driven methods such as terrestrial biosphere modeling are used to fill in these gaps in undersampled pools and non-inventoried geographies. Finally, the regional budget is closed by estimating the lateral flux of terrestrial carbon to the aquatic system, typically constrained by concentration measurements of the terrestrial-derived carbon in the water leaving stream and river systems.

Estimation of forest carbon stock change for these accounting efforts often make use of repeated measures of ground-based field plots and continuous forest inventory programs at the national-level. Many countries have established national forest inventory (NFI) programs with repeated measurement of permanent sample plots (Pan et al., 2011). NFIs also typically track the harvest, removal, and fate of HWPs and their emissions as part of the overall budget assessments and reporting programs. Large-area forest inventories, however, are challenging to conduct and require significant resources. Indeed, there are key pools and processes that are under-sampled (such as below-ground carbon and aquatic exports) and large areas of remote and “unmanaged” forest that are not included in formal inventories. Moreover, the re-measurement cycle can be too long to attribute finer-scale process and there is limited predictive capability to assess future scenarios. Here, remote sensing and modeling approaches can be used to help fill in these spatial and temporal gaps in carbon budget accounting and process-based knowledge of forest carbon dynamics.

THE ROLE OF MODELING IN FOREST CARBON ASSESSMENTS

Models are used to understand forest carbon dynamics because the biophysical, socio-economic, and geographic factors that influence forest carbon are complex (Rindfuss et al., 2008; Lambin et al., 2001). They provide a structured way to investigate forest use and a methodology for estimating historical and future carbon stocks and fluxes because of management and other socioeconomic (e.g., timber demand, recreation use) and biophysical drivers (e.g, climate, pests, disease).

What Are Models Good For?

Forest carbon models are often developed to inform government, community, industry, and landowner level decision making by highlighting the probabilities of future alternative outcomes, issues, and opportunities associated with various policies, natural or anthropogenic shocks, and/or drivers to the forest ecosystem. Models can also inform the direction of research, provide tools to answer research questions, and express results in a repeatable and robust way that helps provide a better understanding of how forest carbon can be influenced by a range of drivers. The quality of a model and the robustness of its conclusions are tested within the scientific community before model results are made available to the wider society. This helps ensure that modelling, and scientific activity in general, upholds the standards of rigor that are expected by the scientific community.

There are a variety of forest carbon models because different models are required to answer different questions, to model different situations and to work at various levels of detail. These models make different assumptions and use different data and methodologies. As forest carbon dynamics are typically too complex for any one model to capture fully, using multiple models in combination can provide a more comprehensive and robust understanding of forest ecosystem function. In addition, cross model comparisons can be used to help validate the different models. When used appropriately, the variety of available models should be seen as a strength rather than as a weakness.

Box 1. What Is a Model?

A model is a simplified representation of reality that focuses on the key factors and (cause-and-effect) relationships of a phenomenon. Models describe how these factors are related, and the strengths of the different relationships.

Models fall into two broad classifications: a) theoretical or conceptual models and b) numerical or computer models. Theoretical or conceptual models provide a representation of reality that emphasizes how the different parts of a system interact without seeking to quantify the magnitude of any interactions. Examples of theoretical or conceptual models include flow diagrams and systems of algebraic equations, and typically are used when empirical data are not available. Numerical and computer models provide representations of reality that both describe how the different parts of a system interact and quantify the magnitude of these interactions. Numerical models are often developed within the context of a more general theoretical model. Examples include weather forecasts and economic projections. These models are almost always informed by other research activities where data have been collected and analyzed. The specific forest carbon models discussed in this report all sit within the numerical or computer model classification.

Models are used to understand and quantify forest carbon stocks and fluxes because the factors and decisions that influence forest carbon dynamics are complex. This complexity arises from the decision process made by forest managers when determining forest use and management, which are influenced by biophysical and geographic variability, economic uncertainty, and policy constraints.

Several US states have established climate change mitigation or greenhouse gas (GHG) reduction targets. In many states, forests are being considered as a key natural climate solution (NCS) to help meet net GHG emission targets. The extent to which forests can contribute to that goal depends on several factors including the extent and condition of current forest stocks, landowner priorities, and biophysical and socioeconomic stressors on forests. For example, a given state may currently have a relatively high rate of forest carbon sequestration, which is influenced by historical management decisions. However, the extent to which the state can maintain this level of sequestration is uncertain because of various stressors or disturbances (e.g., wildfire, pests, disease, harvesting, etc.) combined with future management decisions in response to these anticipated stressors. In response, agencies may wish to consider implementing policies to incentivize forest management practices that are likely to help maintain or enhance forest carbon sequestration. The policymaking process can be informed via forest carbon modeling. While specific modeling needs may vary by state and/or policy concern, most will be looking for verified and well documented models that have been used in prior applications (and thus have 'agency'), the ability to adapt and modify models to forest conditions unique to the area of interest, and option to apply models in broad and sometimes novel ways.

How can we use models?

Forest carbon models are put to a variety of uses and to answer a wide range of policy questions. As forest management decisions can have environmental, economic, and social consequences, models can be used to better understand the drivers that affect forest carbon dynamics and the consequences of policies that are developed to influence carbon stocks and flows. There are a variety of forest carbon models that can be applied to eastern US forests, so choosing the 'right' model to use depends on the questions of concern and resources available to model and answer them. The use of forest carbon models includes the following:

1. *Models are used to estimate the potential impacts of specific policy.* For example: What is the likely impact of including forest carbon in the state's net greenhouse gas mitigation target? What impact is this likely to have on local and regional timber supply and wood product markets? Who and what will be most affected because of this policy?

2. *Models are used to inform the policy design by investigating alternative courses of action*. For example: How does the cost and effectiveness of increasing forest carbon sequestration vary under different management incentive policies? How likely and quickly can a landowner respond to this new intervention? How will forest carbon change as a result of the policy instrument?

3. *Models are used to diagnose potential issues that could arise in the future.* For example: What are the impacts of external pressures (climate change or timber market condition shifts) on forest management and carbon dynamics? Which forests and/or landowners are most likely to face these stressors? And what patterns of forest management might be encouraged to mitigate the negative stresses?

The most appropriate model(s) to use will largely depend on the question(s) of interest and level of resources (e.g., time, expertise, data) available. Some models are better at producing high resolution spatial estimates of the current state of the forest while others are better for exploring broad drivers on the future of the forest. We expand upon the 'what' and 'how' associated with choosing and utilizing several models available to practitioners and policymakers below.

MODELING APPROACHES TO REGIONAL CARBON BUDGET ESTIMATION

Estimations of land-based carbon budgets over large domains, typically involving a combination of measurements and modeling, can be categorized as either "top-down" (atmosphere-based) approaches, such as eddy-covariance flux observations and atmospheric inversion models, or "bottom-up" (biosphere-based) approaches that include a range of methods from empirical upscaling ground-based measurements and inventory plot information to spatio-temporally extrapolated simulation with numerical, process-based ecosystem models.

Top-down approaches provide a reliable constraint on overall land-atmosphere carbon exchange based on direct measurement of spatial and temporal patterns in CO_2 (and other GHGs) concentrations. Regional-scale estimates of net ecosystem exchange (NEE; i.e., the net exchange of CO_2 between land and atmosphere) are derived from these observations using different techniques ranging from simple boundary-layer budget approaches (Wofsy et al., 1988) to upscaling eddy covariance data (Jung et al., 2009; Xiao et al., 2012) to more complex inverse modeling of atmospheric transport (Gurney et al., 2002). Atmosphere-based estimates are broadly inclusive and treat all surface-atmosphere CO_2 exchange as one integrated flux. However, such estimates have limited attribution information on 1) stock changes within individual components, 2) internal processes, 3) lateral transfers, or 4) the exact location of carbon sinks and sources, which is derived from biosphere-based approaches.

Plot-based measurements serve as the basis for bottom-up approaches – either directly, as input to inventory-based methods (e.g., Birdsey and Heath 1995; Stinson et al., 2011), or indirectly through their use in calibrating ecosystem process models (e.g., McGuire et al., 2001). Although researchers can apply bottom-up approaches at broad scales to estimate flux components individually, evidence suggests there are important carbon pools and fluxes that are under-sampled, have large or unknown uncertainties, and are not inventoried or modeled at all (Hayes et al., 2012; King et al., 2015). Despite these limitations, bottom-up methods (e.g., inventories) typically are cited in broader-scale carbon cycle assessments (e.g., Goodale et al., 2002; Pacala et al., 2007; Pan et al., 2011) that favor these approaches for their use of substantial amounts of measurements, ability to track the total change in ecosystem carbon pools, and comparability among estimates.

Forest Inventory Models

Regional or national forest inventory models are based on ground-based measures coupled with statistical methods where sample plots are randomly or systematically located across a forested area of the domain, or at least the “managed” portions therein (McRoberts et al., 2010). A census of the trees is made at each plot along with various measurements of each including species, diameter, height, and condition that can then be used in allometric equations to estimate tree biomass (Xing et al., 2019). Additional measurements are taken at each plot or a subset of the plots to estimate plot-level carbon by including other important pools such as understory vegetation, woody debris, litter, and soils (Banfield et al., 2002; Shaw et al., 2014). Estimates of total forest carbon can be imputed over the plot network (Wilson et al., 2013), often making use of remote sensing (Beaudoin et al., 2014; Kangas et al., 2018). The plot-based carbon estimates are then scaled up to the national-level by some type of modeling approach, which differs across the NFIs of different countries (Kurz et al., 2013; Woodall et al., 2011).

Changes in the stocks of live and dead organic matter pools in the forest are determined from NFIs by either direct plot re-measurement and/or with some combination of remote sensing and spatial modeling methods. The “stock-difference” approach used in the U.S. Forest Inventory and Analysis (FIA) program, for example, is based on the difference between complete inventories at two points in time, thus capturing the total change in ecosystem carbon (Hou et al., 2021). In the Nordic countries, carbon stock change is estimated from the NFIs based on re-measurement of a subset of each nation’s permanent plot network on a 5-year cycle (Kangas et al., 2018). Area-based modeling using airborne laser scanning (ALS) data is a major component of the inventories in Norway, Finland, and Sweden (Maltamo & Packalen, 2014; Næsset, 2014). Alternatively, Canada’s national forest carbon inventory is based on the “gain-loss” method, which starts with a complete inventory that is then updated by modeling forward the components of change, including growth, mortality, decomposition, and disturbance (Kurz et al., 2009; Stinson et al., 2011).

Carbon Bookkeeping Models

In many nations, formal and systematic forest inventories are not conducted. Instead, regional-scale budget estimates for GHG reporting have been drawn from “bookkeeping” accounting studies (Masera et al., 1997) of carbon stock change resulting from land-use change and national reports (de Jong et al., 2010). This approach is used to estimate forest sector emissions by multiplying the area of land impacted, or activity data, by the carbon content per unit area, or emission factor (GFOI, 2016). Bookkeeping models for carbon accounting range from broad-scale assessments based on coarse, regional-level statistics (Houghton et al. 1987; Goodale et al., 2002) to more spatially-explicit estimates using remote sensing (Tang et al., 2020). Bookkeeping models (Houghton et al., 2001; Houghton, 1999) typically track annual carbon emissions and uptake by multiplying a set of emission factors times spatially aggregated estimates of land cover changes (e.g., Kuemmerle et al., 2011; Olofsson et al., 2011). These assessments provide only regionally aggregated estimates of carbon emissions and uptake, but the same concepts can be implemented at a management resolution (e.g., 30 m) by including finer-resolution carbon stock and activity data derived from remote sensing observations (Gong et al., 2022).

The Role of Remote Sensing

The amount and spatial coverage of available, field-based measurement data for forest carbon stocks tend to be limited by accessibility, regional extent, and institutional investment in inventory and research. More formal forest inventories have historically been driven by the economic value of management for wood fiber and were not necessarily designed to produce a regional-scale GHG budget. Limitations such as the length of time between inventories cause inconsistencies in reporting while introducing uncertainties in attributing growth, mortality, and disturbance. Furthermore, many important forest carbon pools, particularly belowground, are not consistently or sufficiently sampled (Bai & Fernandez, 2020). To improve monitoring, reporting, and verification systems, remote sensing and modeling can be used to help fill in these spatial and temporal gaps in carbon budget accounting (Lister et al., 2020). Remote sensing provides powerful tools for extending and enhancing forest measurements and models to regional scales for a wide array of key attributes (Masek et al., 2015; White et al., 2016). This includes a variety of potential methodologies including nearest-neighbor spatial imputation from

Landsat (e.g., McRoberts, 2008), airborne LiDAR-driven Enhanced Forest Inventories (White et al., 2013; Ayrey et al., 2021), spaceborne-LiDAR for monitoring biomass carbon (Dubayah et al., 2022), and pixel-based mapping of forest type and condition based on airborne image analysis (Lister et al. 2020). The challenge is to integrate the measurement accuracy and reliability of plot and inventory data with the spatial and temporal breadth and consistency of remote sensing scaling approaches, while quantifying and understanding the sources of uncertainty.

Mechanistic Models

Beyond the basic accounting of changes in carbon stocks between two points in time, many research, management, and planning applications require a more detailed treatment of the processes responsible for those changes. Such applications employ mechanistic models that simulate the processes of forest growth, mortality, disturbance, and succession at various levels of complexity and over a range of spatial and temporal scales. There exists a wide array of models, the variation reflecting the different applications for which they were developed. Their structure and operation will depend on the data required to drive the model, the mode of simulation (diagnostic versus prognostic), spatial resolution and time step, and the number and detail of processes included. Considering the incredible breadth of models, applying such tools to carbon assessment for the managed forest sector requires implementing key mechanisms related to harvest and silvicultural treatment, the impacts of a variety of disturbances, simulating the ecological processes of forest succession, and tracking the fate and lifetimes of forest products, among others important for different applications.

Individual-based models built on the “gap concept” for simulating vegetation dynamics related to forest succession and resource competition have a long history of development for growth-and-yield applications at the stand-level (Weiskittel et al., 2011). Forest gap models simulate how species composition and structure will change in response to natural succession, disturbances, and silvicultural treatment (Shugart, 2003). They are commonly used to “grow” field-measured plots at different points in time to reconstruct historical stand conditions, compare with contemporary remote sensing data, or make projections of future resource inventories. These projections typically provide a range of estimated stand-level attributes including tree species volumes, biomass, density, canopy cover, harvest yields, and fuel loads.

Where these individual-based models are limited to plot- and stand-level inference, Forest Landscape Models (FLMs) extend the vegetation gap dynamics concept to broader spatial scales for regional assessments. FLMs are a class of mechanistic models designed to simulate the spatio-temporal dynamics of forest ecosystems at large spatial scales and have become increasingly effective tools for assessing the impacts of both natural and anthropogenic disturbance (Xu et al., 2009). These dynamic models operate at high spatial resolution, making them particularly amenable to capturing ecological dynamics that stem from, or are constrained by, forest conditions as observed by remote sensing. In typical applications, forest landscape models are used to compare alternative disturbance or management scenarios in order to explore system behavior and provide strategic decision support (Gustafson et al., 2011).

Terrestrial biosphere models (TBMs) represent a broad category of models that simulate a myriad of ecosystem processes, their internal feedbacks, and response to external forcings (Fisher et al., 2014). For their initialization, parameterization and validation, TBMs rely on *in situ* measurements and remotely-sensed observations of a whole suite of ecosystem properties at representative locations. TBMs can operate diagnostically, where ecosystem production is driven by remote sensing data (Potter et al., 2007), or prognostically by simulating photosynthesis based on calculations internal to the model (McGuire et al., 1992). These ecosystem process simulations can be extrapolated to regional carbon budget estimates using maps of plant functional types and analyzed or predicted over time using climate, land use, disturbance, and other forcing data. Simulation experiments with TBMs allow scientists to explore hypotheses related to driver sensitivity and attribution of carbon dynamics in managed forests and other ecosystems. To be exercised in carbon management applications, however, TBMs need to tackle challenging issues of scale, particularly in capturing the high sub-grid heterogeneity of structure and processes in complex forest ecosystems. TBM frameworks are increasingly working toward the development and application of individual-based models that incorporate tree demography and dynamics.

A FOREST CARBON MODEL SELECTION FRAMEWORK

There are a broad range of questions to consider when selecting a forest carbon model**:**

- What forest carbon pools (e.g., aboveground, belowground, harvested wood products) does the model account for?
- At what spatial scale (e.g., pixel, plot, stand, parcel, county, state, etc.) does the model simulate ecosystem carbon stocks and fluxes?
- At what timestep (e.g., daily, annual, decadal, etc.) does the model estimate forest carbon dynamics?
- Can the model incorporate policy relevant management alternatives (e.g., silvicultural systems, best management practices) of interest to decision makers?
- How does the model incorporate ecosystem disturbances to accommodate the policy objectives?
- How does the model account for carbon stored in harvested wood products?
- How does model parameterization compare to the available data for an intended use? Are there realistic options to enhance data availability to result in successful utilization of the model?
- How sensitive is model parameterization to measurement methodologies or other user-based inputs and assumptions?
- What are the levels of uncertainty in the output of any of the models compared to the goals of the user?
- For applications where total atmospheric greenhouse gas reductions are a primary goal, how does the model accommodate non-CO_2 greenhouse gases (e.g., CH_4, N_2O, etc.)?
- To what extent does the model incorporate socioeconomic drivers (e.g., market demand, land use change, etc.) on forest carbon stocks and fluxes?

- ❖ Does the model account for potential impacts (e.g., leakage) outside of the geographic area of interest?
- ❖ What software licenses and computer resources are required to run the model?
- ❖ What level of skill and resources are required to use the model and how does that compare to the quality and utility of the model output to inform decision making?

The level of detail required will vary by the policy and management questions and staff, financial, and time resources available to answer the question. For example, it may not be possible to build a detailed state-level forest sector model from scratch if questions need to be answered in a matter of days or weeks. However, some of the key questions such as 'what is the current forest carbon stock for the state' can be approximated without the use of an extremely detailed dynamic, forward-looking forest carbon model. To facilitate state agencies in choosing the 'most appropriate' model, we have developed a forest carbon modeling decision support framework that summarizes the key components of these models.

An overview of the model components that we identified for models considered applicable to the eastern US is listed in **Table 1** along with how these categories are populated using the LANDIS-II model as an illustrative example.

Table 2 lists the specific criteria that the framework developed to assist with model selection based on agency resources, user knowledge, and time constraints. Each individual criteria were then scored on a scale of 0-10, where a score of zero indicates that it does not have any capability to meet that criterion, and a 10 indicates very high capability. These individual criterion scores were then aggregated into three key criterion categories – usability, complexity, and analytical capability – which represent an average of the individual scores within a given category. These aggregate criteria scores were then averaged to develop an overall model criteria score that was also presented on a scale of 0-10.

Table 1. Key components of forest carbon models with LANDIS-II example

Component	Description	Example using LANDIS-II
Statement of purpose	What model is primarily developed to do	Designed to model custom disturbance and succession for large landscapes. Most common models examine seed dispersal, carbon dynamics, forest management, and climate change impacts.
Model Type	Main model category (bookkeeping, economic, etc.) and characteristics (e.g., landscape, stand)	Landscape, ecological
Model methodology	Primary model approach (simulation, optimization, etc.)	Simulation
Simulation Mode	Temporal focus of the model (i.e., past, present, future)	Future / prognostic
Temporal Resolution	Resolution that model is parameterized at	Annual
Temporal Extent	Typical time steps that model output is produced at	Decadal to multi-century timesteps
Spatial Resolution	Geographical resolution of model	User-defined stands and cohorts (resolution varies)
Spatial Extent	Typical geographical extent of model	Landscape, hundreds to millions of acres
Carbon Pools	Carbon pools included in model accounted	Aboveground growing stock
Forest Ecosystems	Forest ecosystems / species included in default model	User-defined
Other key outputs	Other key outputs besides carbon pools that are captured in the model	Harvested biomass
Silvicultural Practices	How the model accounts for silvicultural practices / forest management	User-defined (e.g., clearcut, partial removal, thinning, etc.)
Disturbance	Whether model accounts for ecological disturbances like fire, pest, and disease.	Yes
Climate Sensitivity	Whether the model accounts climate change	Yes, with user-defined climate projections
Deterministic v. Stochastic Process	Stochastic: includes a random component that uses a distribution as one of the inputs and can produce a distribution for the output. Deterministic: uses numbers as inputs and produces numbers as outputs.	Quasi-stochastic
Data Requirements	Key user-provided data required to parameterize and run model	plot/polygon level vegetation information; optional: climate data, soil data
Accessibility	Software and licensing requirements	Open source, available via model website
Computing Requirements	Other computing requirements to parameterize and run model	text file reader; optional: GIS software (for raster data)
Primary user	Personnel model primarily developed to be used by (e.g., ecologists, economists, computer scientist, etc.).	Forest ecologist, computer scientist
Customizability	The extent to which the model can be customized for a specific geographical area, driver, policy, etc.	Highly customizable; several model extensions; varying spatial scales and resolutions,
Learning time	Likely amount of time required to learn how to use model	Months
State policy utility	Utility of the model for state-level policymaking	High, but could require significant resources to parameterize and calibrate, especially if interested in complex silvicultural systems.
Latest model version	Latest version of the model, and when last updated.	v7.0 (2018)
Relevant Applications	Examples of where model has been applied in the Eastern US	Northern Maine, Vermont
Model Documentation	Link to website with more details	https://www.landis-ii.org/

Table 2. Eastern forest carbon model selection criteria

Criteria	**Category**	**Options / Components in Criteria Scoring**
Accessibility	Usability	Open Source; Software; License
Learning Curve	Usability	Low; Medium; High
Data requirements	Usability	Low; Medium; High
Spatial resolution	Complexity	Pixel; Plot; Stand; Landscape; Regional
Spatial extent	Complexity	Varies
Temporal resolution	Complexity	Daily; Monthly; Annual; Greater than annual
Temporal extent	Complexity	Daily; Monthly; Annual; Greater than annual
Silvicultural systems supported	Complexity	Yes / No
Forest Ecosystem Carbon Pools	Complexity; Analytics	Aboveground; Belowground ; Soil; Coarse woody debris
Timber Harvest	Complexity	Yes / No
Harvested wood products pools	Complexity; Analytics	Yes / No
Scenario analysis	Analytics	Yes / No
Economic drivers	Analytics	Yes / No
Climate sensitivity	Analytics	Yes / No
Fire, pest, disease sensitivity	Analytics	Yes / No

Forest Carbon Models to Consider for the Eastern US

Our model compilation and assessment exercise identified at least 15 models that could be used to estimate forest carbon in Eastern US forests with varying degrees of usability (access), complexity, and analytical capability. A list of the models and their purpose statement is listed in Table 3. We expand upon some of the key models used in the region below.

Table 3. Eastern forest carbon models to consider for state-level policy analysis

Model Name	***Model type***	***Model Statement of Purpose***
LANDIS-II	Ecological simulation	Designed to model custom disturbance and succession for large landscapes. Most common models examine seed dispersal, carbon dynamics, forest management and climate change affects. LANDIS II uses a biomass module which calculates aboveground mortality, net primary productivity, and decay of woody biomass. The biomass module is on an annual time-step. Net primary productivity which would capture forest growth and yield is assumed to reach an equilibrium in which growth equals mortality and biomass ceases to increase. Net primary productivity in addition to decay, are static variables for each species and ecoregion. Actual primary productivity was calculated for each region without information about previous disturbance.
CBM-CFS3	Empirical stock and change model	The CBM-CFS3 is a landscape-level model of forest ecosystem carbon dynamics that forest managers and analysts can use to assess the carbon stocks and changes in carbon stocks in their operational forest areas. Although developed primarily to assess carbon dynamics at the operational scale, the model can also be used to explore carbon dynamics for smaller areas, down to the stand level. The model can be used to assess past changes in carbon stocks using information on management actions and natural disturbances that have already occurred or to evaluate future changes that would result from scenarios of management actions and natural disturbances. The CBM-CFS3 accounts for carbon stocks and stock changes in tree biomass and dead organic matter (DOM) pools.
FVS	Forest stand simulator driving by statistical equations	The purpose of the model is to assess how forest vegetation changes given various disturbances, succession, and management actions. The Sub-Carbon extension was created because there was an increased interest and need in tracking forest carbon. Trying to do this at a large scale is incredibly challenging, so the sub-model extension was created with the intention of tracking management effects on forest carbon on smaller scales. The model was additionally created with the intention of making it accessible for land managers who want to assess how current or alternative management actions would affect forest carbon.
FASOM	Regional Economic, Dynamic Optimization land use	The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States. The FASOM model initially was developed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees but also has been applied to a wider range of forest and agricultural sector policy scenarios.

3PG	Empirical relationships based on simplified physiological relationships	The 3-PG model (Physiological Processes Predicting Growth) was developed to bridge the gap between conventional, mensuration-based growth and yield, and process-based carbon balance models. The output variables it produces are of interest and relevance to forest managers.
ForGATE	Forest sector GHG assessment tool	ForGATE is a forest sector greenhouse gas (GHG) accounting tool designed primarily to communicate information relevant to the evaluation of projected net GHG exchange in the context of Maine's forests, the Northeast forest sector, and alternative national or regional carbon (C) accounting guidelines. It also provides forest managers and policy makers with an easy-to-use tool for examining the relative merit (C credit revenue vs. project cost) of C offset projects and forest sector life cycle GHG accounting
Woodstock / REMSOFT	Optimization tool	Woodstock is an integrated optimization modeling platform with robust prescriptive analytics capabilities that can help you improve decisions, resource and asset management.
Open Stand Model	Forest stand simulator	The Open Stand Model is a generic, open source software platform for growing stands or plots forward in time. Its role is to model survival, growth and regeneration of trees over very long time periods and under alternative management.
GTM	Economic, Dynamic Optimization	GTM is an economic model capable of examining global forestry land-use, management, and trade responses to policies. In responding to a policy, the model captures afforestation, forest management, and avoided deforestation behavior. The model estimates harvests in industrial forests and inaccessible forests, timberland management intensity, and plantation establishment, all important components of both future timber supply and carbon flux. The model also captures global market interactions, global timber supply and the associated carbon accounting. It solves in 10-year increments and terminal conditions are imposed after 200 years. The model has been updated over time and used in a variety of policy analyses.
LURA	Economic, Static Optimization	The purpose of LURA is to simulate future macroeconomic conditions to understand their impacts on localized forest management and forest biomass CO2. LURA uses FIA plots as input, making supply and demand spatial for the model. Macroeconomic conditions can have large effects on forest carbon because as the economy grows, forest carbon tends to diminish (Latta et al. 2018). LURA can also be used to understand forest biomass utilization at regional and national scales.

TEM6	Processed-based, ecosystem simulation	Initial purpose of the model was to estimate how NPP will change given global atmospheric and land use changes. TEM estimates temporal and spatial distribution of major carbon and nitrogen pools at a global scale. TEM6 incorporates a dynamic cohort structure that can simulate the impacts of multiple disturbances on carbon stocks and fluxes.
CLM5 / CLM-FATES	Global climate model	The purpose of the model is to quantify ecological climatology. CLM's website defines 'ecological climatology' as the interdisciplinary field of how natural and human interactions with vegetation affect climate. Through the study of physical, chemical, and biological interactions, the model's purpose is to understand how terrestrial ecosystems affects and are affected by climate across various temporal and spatial scales. The assumption is that the cycling of physical, chemical, water, energy, etc. are important elements of determining climate.
Ecosystem Demography (ED2)	cohort-level, dynamic vegetation	ED2.2 is designed to run: 1) as a stand-alone land surface model over small list of specified locations, 2) as a stand-alone land surface model over a regional grid - separated into spatially-contiguous tiles of polygons, or 3) coupled with an atmospheric model over a regional grid - polygons are designed to match each atmospheric grid cell.
Biome-BGC	Mechanistic terrestrial ecosystem process model	Purpose is to examine global and regional interactions of climate, disturbance, and biogeochemical cycles. Hidy et al. (2016) created Biome BBCGSuMo to address existing uncertainties with previous Biome-BGC. They specifically addressed the lack of management options for simulations and the simplistic soil module; they added more management options (including thinning) and a 7-layer soil module. They additionally added capability to parameterize soil water saturation (prior versions of Biome-BGC did not have the capability to reach saturation).
PnET	Empirical relationships based on simplified physiological relationships	PnET is a suite of three nested computer models which provide a modular approach to simulating the carbon, water and nitrogen dynamics of forest ecosystems.

More details available here.

A summary of the criteria scores based on model usability (access), complexity, and analytical capability is presented in Table 4 and **Figure 2**. These indices highlight how models that may have high analytical capabilities and complexity (e.g., carbon pools, high spatial and temporal resolution, account for multiple disturbances, etc.) may also have relatively low usability due to the nature of their design. Note that these scores are intended to highlight the variability of selection criteria both within and across models. Interested users should refer to the individual model summary and disaggregated criteria information for a more comprehensive overview of each model.

Table 4. Eastern forest carbon model criteria scores (0 = very low; 10 = very high)

Model Name	**Usability Score**	**Complexity Score**	**Analytical Capability Score**	**Total Score**
FVS	7.0	9.6	8.6	**8.4**
LANDIS-II	6.0	9.6	8.1	**7.9**
ForGATE	10.0	7.6	5.7	**7.8**
GTM	5.0	8.0	10.0	**7.7**
TEM6	6.7	8.0	8.3	**7.7**
CBM-CFS3	5.3	9.0	8.6	**7.6**
Open Stand Model	6.7	8.9	6.7	**7.4**
FASOM	3.3	8.0	10.0	**7.1**
Ecosystem Demography (ED2)	8.3	7.0	3.9	**6.4**
PnET	8.3	6.5	4.0	**6.3**
Biome-BGC	8.3	6.3	4.0	**6.2**
3PG	6.7	6.0	5.4	**6.0**
CLM5 / CLM-FATES	6.7	5.6	5.4	**5.9**
LURA	3.3	7.3	6.7	**5.8**
Woodstock / REMSOFT	0.3	7.9	6.7	**5.0**

More details available here.

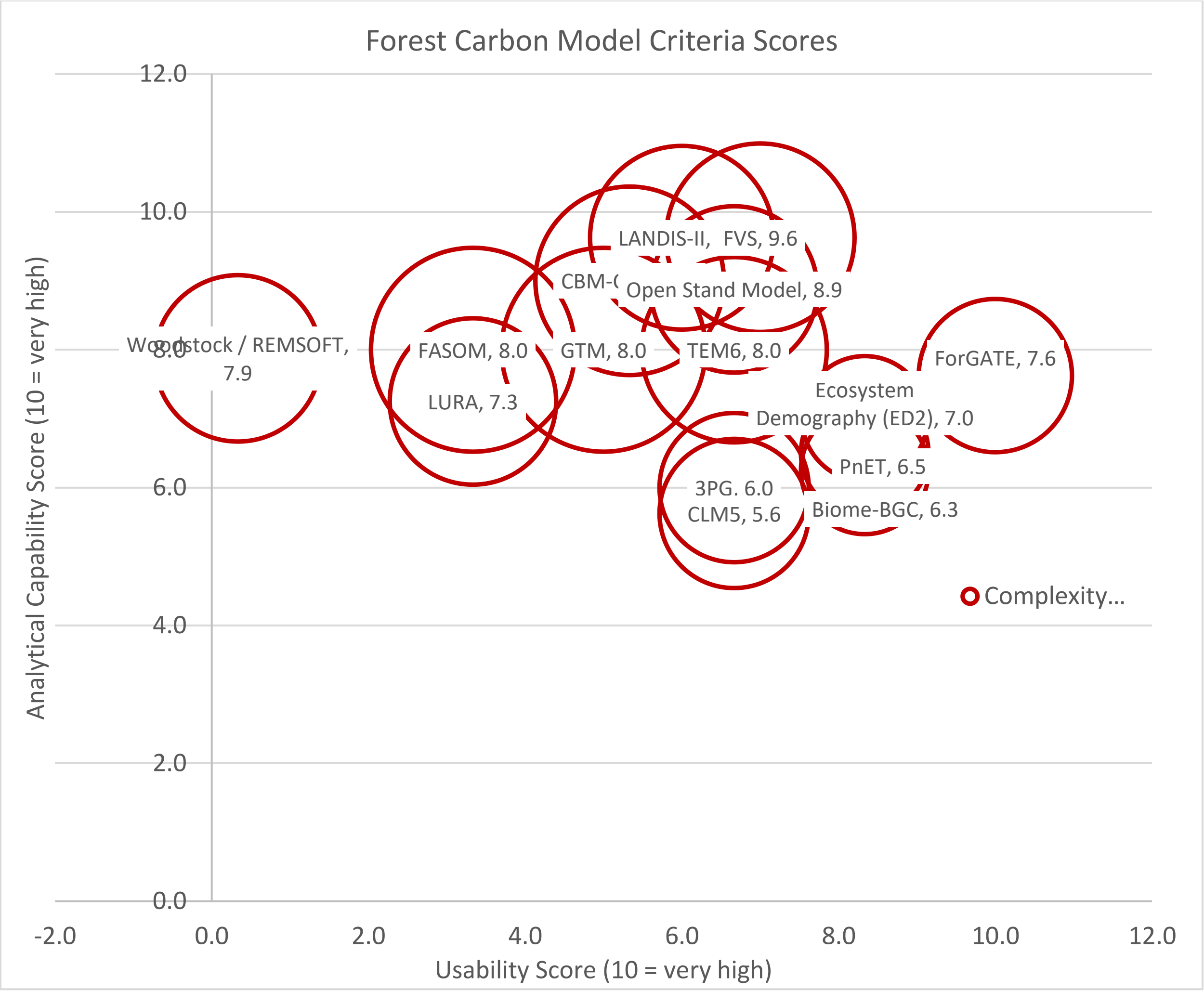

Figure 2. Eastern forest carbon model criteria scores by key aggregate criterion (0 = very low; 10 = very high). Note: larger circles indicate higher complexity scores.

In the remainder of this section, we provide a short list of some of the key models used for projecting forest carbon in the US. Our focus in providing this list is to highlight the differences between each model, their relative strengths, and when / why you would use a particular model. We limit the scope of this list to specific models currently in use for modelling forest carbon in managed landscapes. Key models to consider include LANDIS-II, Forest Vegetation Simulator (FVS), and the Canadian Forest Services Carbon Budget Model (CBM-CFS3).

LANDIS-II

The original LANDIS model has been developed since the early 1990s by scientists at many institutions, including the University of Wisconsin, U.S. Forest Service, and Portland State University. The current LANDIS-II model extended the functionality of LANDIS, while providing additional flexibility and functionality (Scheller et al. 2007). The model has been extensively used for scientific ecological research across the world. LANDIS-II is not owned by any person or entity;

it is free, open-source, and any scientist or ecological researcher interested in using the model may use the model that is fully available online (https://github.com/LANDIS-II-Foundation).

LANDIS-II models multiple disturbances (fire, wind, harvesting, insects) and forest succession across large landscapes. The LANDIS-II model utilizes a cellular automaton approach, whereby the landscape is composed of many spatially interactive cells. Each cell is assigned to an ecoregion with homogeneous soil and climate. Trees are represented within LANDIS-II as species and age cohorts. Disturbances interact through their collective effects on forest succession, and through their influence on other system properties (e.g., fine and coarse fuel accumulation).

Each ecological process is represented as an individual dynamic linkable library that can be added, modified, or replaced as needed. The model allows new components to be added at-will. Users may select a time step that best fits the temporal scale of succession and disturbance within the modeled ecosystem. The model is applicable to broad spatial and temporal scales, but can be sensitive to certain model parameters (Simons-Legaard et al. 2015) and needs certain modifications for complex simulations (Simons-Legaard et al. 2021). Example applications relevant to the Eastern US study area include local forests in VT (Nevins et al. 2021) and WI (Scheller et al. 2011), sub-state analyses in ME (Daigneault et al. 2021), WI and MN (Duveneck et al. 2014), and GA (Flanagan et al. 2019), and a regional assessment for New England (MacLean et al. 2021).

FVS

The Forest Vegetation Simulator (FVS) is widely used stand-level national growth and yield model that is developed and maintained by the US Forest Service, Forest Management Service Center. The primary intent of FVS is to support forest projections and planning for US Forest Service National Forests, while it is also used by forest industry, researchers, and NGOs. The model is well documented with specific geographic variants across the US (https://www.fs.usda.gov/fvs/) and is open-source that is freely available online (https://sourceforge.net/projects/open-fvs/) with an active user community.

Although the specific model architecture can vary by the different variants, the general model structure and functionality is consistent with the description provided in Crookston and Dixon (2005). The model requires a 'treelist' determined from basic forest inventory methods and additional site-level attributes. The model effectively projects the treelist forward in time by directly accounting for tree-level growth and mortality. A variety of model extensions allow for specific ecological and economic calculations including carbon via the Fire and Fuels Extension (FFE; Reinhardt and Crookston 2003). FFE estimates the amount of carbon stored in various forest stand components, such as standing live and dead trees and surface fuels, over time. Consequently, the model is approved for forest carbon offset projects and has been widely used for this purpose. FVS has been modified to account for climate change (Crookston et al. 2010), but this is only currently available for the western US.

FVS has been applied to assess forest carbon impacts in several areas of the Eastern US, often at a plot, stand, or forest-type level with the expectation that estimates could be expanded to represent a larger geographical area. Relevant applications include fire management of mixed oak forests in Pennsylvania (Zhao et al. 2021), quantifying the impact of forest pest management on Maine forest C stocks (Chen et al. 2019; Gunn et al. 2020), estimating the net effects of harvesting frequency, post-harvest retention, and wood products in the Northeast (Nunnery and Keaton, 2010), and assessing the rates of change for carbon pools in managed and unmanaged eastern forests (Gunn et al. 2014).

CBM-CFS3

The Carbon Budget Model of the Canadian Forest Service version 3 (CBM-CFS3; Kurz et al. 2009) is driven by NFI data that are modeled forward based on the fundamental forest carbon cycle mechanisms related to growth, mortality, and disturbance. The accounting relies heavily on empirical and observational data, including for both forest growth and yield as well as disturbance characterization and mapping. The carbon budget model ingests this information and then simulates annual carbon stock changes in forest biomass. Carbon stock changes in the dead organic matter pools are linked to the better-known biomass dynamics, or net primary productivity. Dead wood, litter and soil are calculated as the mass balances from inputs (through litterfall, biomass turnover, and disturbance inputs) and losses (through decomposition, transfers by harvesting, and losses to the atmosphere during disturbances such as fire).

CBM-CFS3 is a modelling framework that can be used to simulate the dynamics of all forest carbon stocks required for UNFCCC reporting and compliant with IPCC methods outlined in the guidelines of the Intergovernmental Panel on Climate Change. The CBM was originally developed to meet the operational-scale (stand- and landscape-level) forest carbon accounting needs of forest managers and analysts across Canada. Because of its flexibility in parameterization, over time it has been increasingly used for a range of applications, having been employed in carbon budget assessments in more than 25 countries to date. Model applications relevant to the Eastern US include projecting forest carbon stocks under alternative management practices in seven states (Papa and DeLyser 2022), a spatially explicit land use land cover change assessment for the conterminous US (Sleeter et al. 2022), and forest and wood product carbon impacts of managing pest outbreaks in eastern Canada (Hennigar and MacLean, 2010).

SUMMARY AND CONCLUSION

Our assessment found that there are many models to choose from when estimating forest carbon in the Eastern US, and all vary in terms of usability, complexity, and analytical capability. The ultimate choice of what model(s) to use will depend on time and resources as well as the question(s) that are being asked. This report suggests some key criteria that could be used to select models to assist with state-level decision-making. We note that in many cases, it may be advantageous to engage experts beyond just state agency staff on model development and application, especially when working with modeling tools that require specific expertise and large computing resources. We caveat that our quantitative model scoring criteria is primarily based on qualitative expert input and subject to revision as more information and use of experience with these models in the region becomes available. Future work could conduct more formal intermodal comparisons (e.g, Mahnken et al. 2022; Daigneault et al. 2022) using data and models specific to the Eastern US as well as identify opportunities to link forest models for improved interoperability and utilization (Dufour-Kowalski et al. 2012).

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This Report discusses the practice and benefits of forest carbon modeling and is intended for a broad audience. It focuses on model types and specific tools that address the impact of forest processes and their management on carbon stocks and fluxes across multiple pools in response to economic, policy, and environmental conditions.

- Greenhouse gas (GHG) accounting is required for developing climate mitigation policy and fulfilling the requirements of emissions reduction agreements
- Natural and managed forest systems are a critical component of this accounting
- Carbon sequestration in the forest sector contributes to climate mitigation by offsetting some portion of the anthropogenic greenhouse gas emissions from fossil fuel combustion and land use change
- International agreements on climate change mitigation, forest conservation incentive programs, and carbon trading markets are critically dependent on the ability to measure, monitor, report, and verify the impacts of forest management on increasing carbon stores
- Models are used to understand forest carbon dynamics provide a structured way to investigate forest use and a methodology for estimating historical and future carbon stocks and fluxes