REVIEW ARTICLE

J. For. 114(2):134–143
http://dx.doi.org/10.5849/jof.15-019

biomass, carbon & bioenergy

Forest Carbon Calculators: A Review for Managers, Policymakers, and Educators

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Forests play a critical role sequestering atmospheric carbon dioxide, partially offsetting greenhouse gas emissions, and thereby mitigating climate change. Forest management, natural disturbances, and the fate of carbon in wood products strongly influence carbon sequestration and emissions in the forest sector. Government policies, carbon offset and trading programs, and sustainable forestry certification programs make it increasingly important that carbon dynamics are incorporated into forest management decisionmaking. Many analytical tools (which we refer to as forest carbon calculators) have been developed to quantify carbon stores and dynamics in the forest sector, but it can be difficult for potential users to know which carbon calculator(s) may be best for any given application. We review 12 forest carbon calculators, providing a classification and synthesis to assist forest managers, policymakers, and educators. Additionally, we discuss key characteristics missing in existing forest carbon calculators that are needed for current and future forest management decisionmaking.

Keywords: forest carbon calculators, carbon sequestration, management, disturbance

Forests provide invaluable ecosystem services such as wood products, wildlife habitat, nutrient cycling, and recreational opportunities (Daily et al. 1997). One important ecosystem service provided by forests is the sequestering of carbon from the atmosphere, incorporating carbon from atmospheric carbon dioxide (CO_2) into biomass. Forests are the largest terrestrial carbon pool, storing more than 800 billion metric tons of carbon globally (Pan et al. 2011). Forests play a critical role as a carbon sink of atmospheric CO_2 by partially offsetting human-caused greenhouse gas emissions and thereby mitigating climate change (Goodale et al. 2002, Heath et al. 2011, Pan et al. 2011). For example, forests in the United States currently offset approximately 13% of US annual CO_2 emissions (US Environmental Protection Association 2015). Whereas forests can be a carbon sink, deforestation, forest management practices, and natural disturbances such as wildfire and insect outbreaks can weaken the strength of this carbon sink or even turn forests into sources of atmospheric CO_2 (DeFries et al. 2002, Houghton 2003, Kurz et al. 2008, Mitchell et al. 2009). Forest carbon sequestration alone is unlikely to halt rising atmospheric CO_2 concentrations but is one of many components for mitigating human impacts on the global climate system (Intergovernmental Panel on Climate Change 2014). Furthermore, forest carbon dynamics are not just the result of forest growth and disturbance but require integration of many components in the forest sector such as wood products, bioenergy production, and land management policy (Malmsheimer et al. 2011). Given the importance of forests and the forest sector in the global carbon cycle, the impacts of management and disturbance agents on forest carbon dynamics are increasingly recognized by government policies and initiatives (California Global Warming Solutions Act 2006, Western Climate Initiative 2007, United Nations Framework Convention on Climate Change 2009), forest carbon offset programs associated with proposed emission reductions (Climate Action Reserve 2010), carbon trading markets (for review, see Peters-Stanley et al. 2013), and forest carbon verification and standards (International Organization for Standardization 2013, American Carbon Registry 2014).

Forest landowners, managers, policymakers, and educators require an understanding of carbon dynamics in forests, specifically how forest management decisions and disturbance agents will affect forest carbon over time. This in turn requires improved "carbon literacy" and the use of analytical tools (i.e., forest carbon calculators)

Received February 22, 2015; accepted June 10, 2015; published online July 16, 2015.

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Acknowledgments. *Funding in support of this article was provided by the USDA Forest Service, Pacific Northwest Research Station and Northern Research Station. We also thank four anonymous reviewers for their helpful reviews of this article.*

to quantify forest carbon pools and fluxes, assess how different management activities and disturbances will impact forest carbon, and determine the fate of carbon in the wood products stream (i.e., life cycle analysis). Forest carbon calculators vary greatly in how they represent ecological, management, and life cycle processes and also vary in their convenience in terms of user interfaces, data required from the user, and outputs generated. This diversity of forest carbon calculators, combined with the absence of a concise synthesis summarizing their strengths and weakness, makes it difficult to determine which forest carbon calculator may best fit a potential user's objectives and constraints. The purpose of this review is to classify and characterize existing forest carbon calculators. Given the wide range of potential user objectives and constraints, our goal is not to rank or grade forest carbon calculators, but rather to provide a concise classification and review to aid potential users in determining for themselves which forest carbon calculator(s) best meet their needs. The target audience for this review includes forest managers, policymakers, and educators. A secondary goal of this review is to assess the general state of forest carbon calculators and determine important limitations and constraints inherent in many or all forest carbon calculators that inhibit their usefulness, perhaps pointing the way for development of new or enhanced calculators.

Methods

The Forest Carbon Calculators

To be included in this assessment, forest carbon calculators had to meet multiple criteria. Forest carbon calculators could be web-driven, spreadsheets, or stand-alone computer programs, but all had to be free and accessible to anyone with a computer and Internet access. Only carbon calculators focused on forest carbon were considered, and we excluded calculators that focused solely on forest product life cycle assessments. We did not consider forest carbon calculators developed from a small number of plots within forests of limited compositional, structural, and management diversity because these highly specialized research or management calculators are unlikely to have the flexibility required for a wide range of forest conditions and user objectives. Many sophisticated ecosystem models used in ecological research were also excluded, because their complexity, potentially high user training time, lack of forestry-specific inputs, and lack of end user support make them unlikely to be used by our target audience. This review focused geographically on calculators designed for forests of North America, although we considered more globally oriented calculators if they were in English. From online searches and conversations with forest carbon experts, we found 12 forest carbon calculators that met our selection criteria (Table 1; Supplemental Table S1).[S]

Classification Overview

Rather than subjectively assessing forest carbon calculators based on expert knowledge or personal bias, our goal was to group forest calculators as objectively as possible based on key characteristics relevant to users with a wide potential range of expertise and applications. Forest carbon calculators were classified into groups based on answers to questions designed to evaluate three broad characteristics that can influence calculator utility for a wide range of potential users: forest system representation, user interface, and output usefulness. Forest system representation can be thought of as a forest carbon calculator's ability to reasonably represent key aspects of ecological, management, and life cycle processes that control carbon pools and fluxes. Examples of system representation include trends in aboveground and belowground forest carbon balance in relation to forest type or stand age, the effects of forest harvest or disturbance on forest carbon; and decomposition rates of wood products in different product and waste streams (i.e., building construction, landfills, bioenergy generation, and recycling). User interface refers to how the user operates the forest carbon calculator (i.e., downloadable spreadsheet, web-driven model, or stand-alone software downloaded to a personal computer), as well as usability issues such as transparency of methods and key assumptions, documentation, training material, and data input requirements. Finally, output usefulness refers to both the flexibility and the type of output data created by the carbon calculator. For example, flexibility may refer to a carbon calculator's ability to compare different management or disturbance scenarios, the ability for outputs to be customized by the user, or whether outputs meet any carbon accounting standards or guidelines. We note that these questions did not assess more technical aspects of the calculators (e.g., non-CO_2 greenhouse gas emissions, parameterization of land-use changes, model initialization of belowground and dead carbon pools, and sensitivity and uncertainty analyses). Although these characteristics and many more are important for evaluating the technical and quantitative aspects of forest carbon calculators, an in-depth technical evaluation was beyond the scope of this review. From the three general groups above, 41 yes/no questions were developed and answered by the authors for each of the 12 forest carbon cal-

Management and Policy Implications

Forest carbon calculators vary in how they represent forest sector carbon dynamics, with important implications for their application in forest management decisionmaking. All reviewed forest carbon calculators estimate aboveground live carbon pools, but many do not estimate carbon fluxes or belowground or dead carbon pools (e.g., roots, soil organic matter, and snags), which respond to forest management activities and natural disturbances differently from aboveground live carbon. Forest managers often want to know how specific silvicultural treatments could affect the carbon balance of forest stands, but only a few forest carbon calculators were designed for and have the capability to be used as forest management decision-support tools. Only a few carbon calculators estimate the impacts of natural disturbances, despite strong impacts of natural disturbances on carbon dynamics. Climate change is anticipated to have an impact on many aspects of forest carbon dynamics (i.e., forest productivity and disturbance regimes), yet few forest carbon calculators incorporate any aspects of climate change impacts on forest sector carbon dynamics. Finally, most carbon calculators include user guides, but few provide tutorials or content designed to improve the carbon literacy of users, and we believe this is especially important for calculators likely to attract first-time users without training or experience in forest sector carbon dynamics.

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.15-019.

Table 1. Forest carbon calculators evaluated in this study.

Acronym	Name	Organization	URL
AFOLU-CC	Agriculture Forestry and Other Land Use Carbon Calculator	US Agency for International Aid and Development	www.afolucarbon.org/
CBM-CFS3	The Operational Scale Carbon Budget Model of the Canadian Forest Sector	Natural Resources Canada	carbon.cfs.nrcan.gc.ca/CBM-CFS3_e.html
CCTv4.0	US Forest Carbon Calculation Tool	USDA Forest Service, Northern Research Station	nrs.fs.fed.us/pubs/2394
COLEv3.0 GCOLE[1] COLE-EZ[1] COLE lite[1]	Carbon Online Estimator	National Council for Air and Stream Improvement, Inc. USDA Forest Service, Northern Research Station	www.ncasi2.org/COLE/
CR-FVS	Carbon Reports using the Forest Vegetation Simulator with the Fires and Fuels Extension	USDA Forest Service	www.fs.fed.us/fmsc/fvs/
FICAT	Forest Industry Carbon Assessment Tool	National Council for Air and Stream Improvement, Inc. Internation Finance Corporation of the World Bank Group	www.ficatmodel.org/landing/index.html
FORGATE	A Forest-Sector GHG Assessment Tool for Maine: Calibration and Case Study	University of New Brunswick, Manomet Center for Conservation Sciences, FORUS Research, USDA Forest Service	www.nrs.fs.fed.us/tools/ForGATE/
FORPLAN	Forest Planner	Ecotrust	forestplanner.ecotrust.org/
FSCC	Forest Sector Carbon Calculator	Oregon State University, USDA Forest Service, Pacific Northwest Research Station	landcarb.forestry.oregonstate.edu
GTR-NE-343 FORCARB2[1]	Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates of Forest Types of the United States	USDA Forest Service, Northern Research Station	nrs.fs.fed.us/pubs/8192
LMS	Landscape Management System	University of Washington, Yale, USDA Forest Service, The Cradle of Forestry in America	landscapemanagementsystem.org/
THPGGEC	Timber Harvest Plan Greenhouse Gas Emissions Calculator	California Department of Forestry and Fire Protection	www.fire.ca.gov/resource_mgt/resource_mgt_forest practice_pubsmemos_memos.php

[1] Denotes functionally similar members within a calculator family that were not included in comparisons.

culators (Table 2; Supplemental Table S2). For specific questions that had potentially conditional or equivocal answers, we consulted with foresters and forest ecologists with working or research knowledge of forest carbon accounting and forest simulation models. We strove to be objective in our reviews and disclose that we were involved developing two of the calculators (FSCC and FORGATE).

Statistical Analysis

All statistical analyses were conducted in PC-ORD, version 6.04 (McCune and Mefford 2011). Using the answers to the 41 questions described above, we classified forest carbon calculators into groups using agglomerative cluster analysis (Orloci 1967, Wishart 1969), determining the number of groups in the cluster analysis using indicator species analysis (ISA) (Dufrêne and Legendre 1997). Following Dufrêne and Legendre (1997), we also used indicator values from ISA to determine which characteristics (answers to questions) were most important in determining group membership. We visualized relative similarities and differences of forest carbon calculators with respect to surveyed characteristics using nonmetric multidimensional scaling (NMS) ordination (Kruskal 1964, Mather 1976). For details regarding all statistical analyses, see the online supplemental material.

Results

Forest carbon calculators clustered best into six groups (Figure 1; Supplemental Figure S1). There were four forest carbon calculators in group 1 (AFOLU-CC, CCTv4.0, COLEv3.0, and FICAT), one calculator each in group 2 (FORPLAN) and group 3 (THPGGEC), two calculators in group 4 (FORGATE and GTR-NE-343), one calculator in group 5 (LMS), and three calculators in group 6 (CBM-CFS3, CR-FVS, and FSCC). Indicator species analysis found six significant and three suggestive characteristics that defined forest carbon calculator groups (Supplemental Table S3), all of which were related to ecological and management system representation. NMS ordination described 89.6% of the cumulative proportion of variance in the original data, predominantly along the first ordination axis. The NMS ordination indicates that forest carbon calculators within groups have more similar characteristics than calculators between groups (Figure 2), whereas both the NMS ordination and cluster analysis dendrogram suggest that the groups can be broadly assigned to three larger classes.

Discussion

Broadly, our analysis found three major classes of forest carbon calculators following a gradient from low to high system representation (i.e., representation of ecological patterns and processes, forest management activities and natural disturbances, and the wood products life cycle). Within these three classes we found six distinct groups of forest carbon calculators. Our discussion below focuses on the key characteristics and potential applications of each group of forest carbon calculators (summarized in Table 3), which we believe will aid potential users. It is important to note that our classification and synthesis do not represent a grading of carbon calculators, especially because many of them were developed for different forest

Table 2. Survey questions for forest carbon calculators.

Question no.	Question group	Question description
1	System representation (ecological)	Does it quantify stand live forest C pools?
2		Does it quantify stand live forest C fluxes?
3		Does it quantify stand dead forest C pools?
4		Does it quantify stand dead forest C fluxes?
5		Does it quantify both stand above- and belowground live forest C pools?
6		Does it quantify both stand above- and belowground dead forest C pools?
7		Does it directly incorporate the primary limiting factors?
8		Does it incorporate effects of natural disturbance events/regimes on forest C?
9		Can effects of climate change on forest C pools and fluxes be quantified?
10		Can a range of forest types or ecological regions be modeled?
11		Can the user specify stand level treatments?
12		Can the user specify the area of treatments?
13		Can the user treat landscapes (multiple stands with different treatments or treatment regimes)?
14	System representation (forest management)	Can the user specify the treatment intensity (percentage of stand basal area [BA], board feet [BF], cover, leaf area index [LAI])?
15		Can the user specify the treatment rotation length or interval?
16		Can the user specify additional treatment details, such as diameter limits, species, etc.?
17		Can the user specify any postharvest site preparation?
18		Can the user specify the intensity/magnitude/severity of a natural disturbance event or regime?
19		Can the user specify the frequency or frequency distribution of a natural disturbance event or regime?
20		Can the user specify the size or size distribution of a natural disturbance event or regime?
21	System representation (product life cycle)	Is the fate of C in forest products quantified throughout the product life cycle?
22		Is the utilization efficiency of harvested wood incorporated into C pools and fluxes?
23		Are the C costs of forest operations incorporated?
24		Does the user need to provide detailed forest inventory data?
25		Is it easy to enter user-provided data into the model?
26	Interface (ease of use)	Can a first-time user have model results within hours?
27		Is it easy for the user to change treatment and/or disturbances events?
28		Can the user design their own specific treatment/disturbance scenarios?
29	Interface (transparency)	Is the calculator's modelling approach described?
30		Are the methods documented and available on same website, or up to date URL links?
31		Are assumptions and/or constraints explicitly stated?
32	Interface (general)	Does it operate from a website?
33		Are there support staff to talk to?
34		Are there in person or online training opportunities (i.e., workshops, webinars, etc.)?
35		Is there an online tutorial with example data?
36	Interface (outputs)	Does it automatically produce output tables?
37		Does it automatically produce output figures?
38		Can model output tables be easily exported to another program?
39		Can output be exported into a geographic information system?
40		Does the output include evaluation of other noncarbon management objectives?
41		Does it state that it meets any carbon accounting standards or guidelines

types, data sources, and user applications. Forest carbon calculators are relatively new, and we expect rapid evolution and proliferation of these analytical tools in the future. We follow discussion of the classes and groups of carbon calculators with key limitations and weaknesses common to all or most calculator groups, with the hope that these limitations and weaknesses will be addressed in the development of the next generation of forest carbon calculators.

Class 1, Low System Complexity: Groups 1A and 1B

All four carbon calculators in this class represent forest carbon with a low degree of system complexity. They provide large-project or regional static estimates of forest carbon, and do not provide stand-level estimates or quantify carbon fluxes over time. Although some can estimate carbon pools over time based on changes in forest age, this is not the same as quantifying carbon flux. For example, none of these carbon calculators quantify heterotrophic respiration, which in some forest types can be greater than CO_2 sequestered by forest regrowth for years to decades after disturbance such as fire or insect mortality, resulting in large and long-lived CO_2 sources to the atmosphere (Dore et al. 2008, Kurz et al. 2008). Although the four carbon calculators in this class were all clustered into one group, they have divergent applications so we treated them as separate subgroups below.

Group 1A: Regional Carbon Pool Estimators (CCTv4.0 and COLEv3.0). These two carbon calculators provide regional to national estimates of forest carbon in the United States using forest inventory data from the US Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis Program. Their strengths lie in robust empirical estimates of aboveground forest carbon pools, and the ability to quantify forest carbon pools across major geographic regions and forest types in the continental United States. However, they do not provide stand-level estimates of forest carbon, nor can a user enter stand-level data from his or her own specific timber cruise or forest inventory. Whereas both of these carbon calculators can provide estimates of carbon pools over time, these are not truly fluxes between pools. Neither calculator simulates forest management activities or natural disturbances, so they cannot be used to quantify carbon changes resulting from harvest or natural disturbances such as wildfire. Because they do not assess impacts of forest management activities on forest carbon, they do not quantify emissions associated with forest harvesting, wood products manufacturing, or the subsequent fate of carbon in the wood products life cycle. These forest carbon calculators are best suited to applications such as estimating current regional or national aboveground live forest carbon pools or possibly extracting baseline forest carbon pool information to parameterize more sophisticated carbon models.

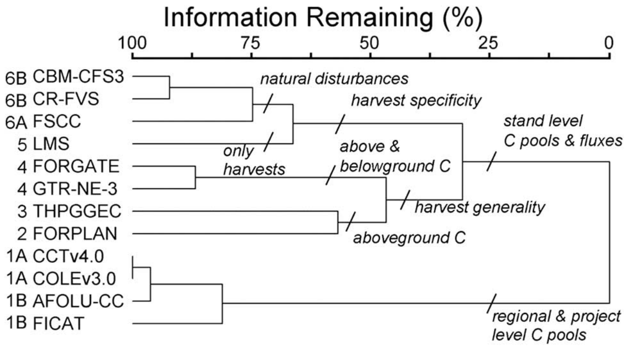

Figure 1. Dendrogram from cluster analysis of forest carbon calculators. The alphanumeric code preceding each carbon calculator denotes class/group membership in the dendrogram as described in the Methods and online supplemental material. The hash marks and associated text show cluster break points at different group levels and associated characteristics. See Table 1 for full names of the forest carbon calculators.

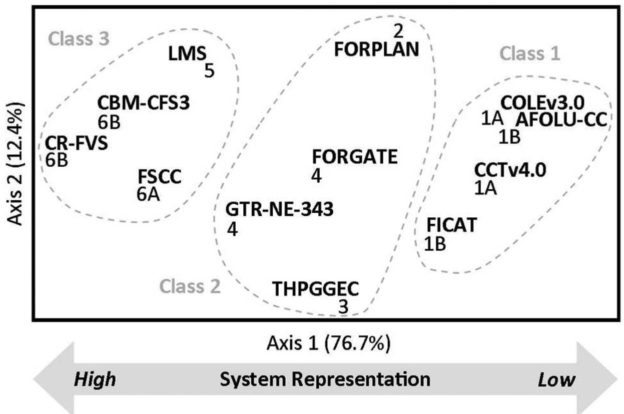

Figure 2. NMS ordination of forest carbon calculators in characteristic space. The alphanumeric codes correspond to class/group membership in Figure 1. Percentage values are the percentage of variance in the original data matrix described by each ordinate axis. See Table 1 for full names of the carbon calculators, and the Discussion for class descriptions. See the online supplemental material for statistical details.

Group 1B: International Forest Management and Development Carbon Estimators (AFOLU-CC and FICAT). Unlike the carbon calculators in group 1A, AFOLU-CC and FICAT are both designed to quantify carbon costs of forest management and therefore explicitly estimate changes in carbon pools resulting from management activities such as harvest and reforestation/afforestation. Neither is designed to examine the carbon consequences of different stand-level treatments but instead focus on large-scale forest management (although with very different applications in mind). Both were designed for international applications, with parameterization of forest carbon pools across a wide range of geographic regions, generic forest types, and generalized management scenarios. AFOLU-CC is specifically designed for application by the US Agency of International Aid and Development to calculate carbon storage and emissions in relation to five main activities associated with international forest development projects (forest protection, forest management, afforestation, reforestation, and agroforestry). AFOLU-CC focuses on how forest development projects may affect carbon storage and emissions at the forest scale but does not quantify the emissions associated with wood harvest or life cycle analysis of the wood products. In contrast, FICAT is geared toward industrial forest projects, with greater emphasis on emissions associated with harvest and life cycle analysis of wood products.

Class 2, Intermediate System Complexity: Groups 2–4

These calculators incorporate greater complexity in their representation of ecological and management dynamics of forest carbon, generally quantifying stand-level carbon pools and fluxes and allowing users more flexibility in assessing the impacts of harvest on carbon dynamics. However, not all calculators in this group estimate belowground carbon, forest management is represented by generalized silvicultural treatments with predetermined harvest intensities and rotation intervals, the impacts of natural disturbances on carbon dynamics are not quantified, and they vary in how they quantify emissions associated with harvesting and the fate of wood products. Three of the four calculators (FORGATE, FORPLAN, and THPGGEC) in this class cover narrow geographic ranges and only a few forest types, greatly restricting their broader utility.

Group 2: FORPLAN. FORPLAN is unique among calculators in its use of a website-driven geographical information system (GIS) user interface. The online GIS interface allows the user to select a particular forest area, which in combination with user-provided stand-level information (stand age, forest type, tree density by species, and size class) is used to automatically and without user involvement parameterize and run a growth-and-yield model (Forest Vegetation Simulator [FVS]) (Dixon 2002). This approach has the benefit of being easy to use while using sophisticated growth-and-yield modeling. FORPLAN can simulate total harvests or thinning, but the range of harvest activities is limited to those most commonly applied in Oregon and Washington, which is also the calculator's geographic extent. FORPLAN also allows the user to assess the financial revenues and costs of harvest operations, although it does not estimate emissions associated with harvest or wood products. FORPLAN is well suited to applications for which forest owners and managers have forest inventory data and want to assess both the carbon and financial effects of generalized management activities on individual stands or management units.

Group 3: Spreadsheet Forest Carbon Management Calculator Requiring User Inventory Data (THPGGEC). THPGGEC was designed for use in the forests of California, although its parameters for growth, harvest, milling, and wood products can be modified for application in other geographic regions and forest types. THPGGEC combines relatively simple representations of forest carbon dynamics with more complete representation of carbon emissions associated with harvest, milling, and wood products life cycle. THPGGEC does not provide default carbon stores or growth rates for any forest

Table 3. Summary of forest carbon calculator key characteristics and applications.

Class	Group	Calculator	Defining characteristics	Applications
Lower ecological and management complexity	1A	CCTv4.0	Forest carbon pools across major geographic regions and forest types Large area forest carbon estimates, little user data required Does not simulate management activities or natural disturbance No emissions associated with harvest, manufacturing, product life cycles	Estimating regional or national forest carbon pools Estimating regional or national forest carbon pools
	1A	COLEv3.0	Forest carbon pools across major geographic regions and forest types Large area forest carbon estimates, little user data required Does not simulate management activities or natural disturbance	
	1B	AFOLU-CC	Forest carbon pools across major geographic regions and forest types Large area forest carbon estimates, little user data required Simulate generalized management activities, not natural disturbances No emissions associated with harvest, manufacturing, product life cycles	Carbon in international forest development projects
	1B	FICAT	Forest carbon pools across major geographic regions and forest types Large area forest carbon estimates, few user data required Simulate generalized management activities, not natural disturbances Emissions associated with harvest, manufacturing, product life cycles	Carbon in international industrial forest sector projects
Intermediate ecological and management complexity	2	FORPLAN	Forest carbon pools in forests of Oregon and Washington Stand-level forest carbon estimates, unique web GIS user interface Simulate common regional management activities, not natural disturbances No emissions associated with harvest, manufacturing, product life cycles	Stand-level carbon and financial assessments of management activities with user-provided data
	3	THPGGEC	Forest sector carbon pools in California Stand-level forest carbon estimates, user stand data required Simulate specific management activities, not natural disturbances Emissions associated with harvest, manufacturing, product life cycles	Forest sector carbon assessments of stand-level management activites with user-provided data
	4	GTR-NE-343	Forest sector carbon pools in major forest types of United States (excluding Alaska) Stand-level and forest sector forest carbon estimates via unlinked lookup tables Harvest activities primarily clearcuts, no natural disturbances Emissions associated with harvest, manufacturing, product life cycles	National forest sector carbon assessments of stand-level without user-provided data
	4	FORGATE	Forest sector carbon pools in major forest types of Maine Stand-level and forest sector forest carbon estimates via linked lookup tables Simulate predetermined set of management activities, no natural disturbances Emissions associated with harvest, manufacturing, product life cycles	Regional forest sector carbon assessments of stand-level without user-provided data
High ecological and management complexity	5	LMS	Forest sector carbon pools in major forest types of Unite States Stand-level and forest sector forest carbon estimates, user-provided data Wide range of user specified management activities, no natural disturbances Emissions associated with harvest, manufacturing, product life cycles Simulates other noncarbon management criteria (wildlife, economic, etc.)	Decision-support tool assessing how management activities may have an impact carbon pools and noncarbon criteria, requires user-provided data
	5	FSCC	Forest sector carbon pools in forests of Oregon Cascades Stand, landscape, and forest sector forest carbon estimates process-based model User inventory data not required Flexible user specified management activities, natural disturbances (wildfire) Emissions associated with harvest, manufacturing, product life cycles	Decision-discussion tool assessing how management activities, natural disturbances, and forest products effect forest sector carbon dynamics that does not require extensive user data
	6	CBM-CFS3	Forest sector carbon pools in forest types across globe, with focus on Canada Stand, landscape, and forest sector forest carbon estimates User inventory data required Flexible user specified management activities, natural disturbances Emissions associated with harvest, manufacturing, product life cycles Incorporates some aspects of climate change that influence carbon dynamics	Decision-support tool assessing how management activities, natural disturbances, and forest products effect forest sector carbon dynamics that requires extensive user data
	6	CR-FVS	Forest sector carbon pools in forests types of the United States, excluding interior Alaska Stand, landscape, and forest sector forest carbon estimates User inventory data required Flexible user-specified management activities, natural disturbances Emissions associated with harvest, manufacturing, product life cycles Incorporates some aspects of climate change that influence carbon dynamics	Decision-support tool assessing how management activities, natural disturbances, and forest products effect forest sector carbon dynamics that requires extensive user data

type; instead the user must provide estimates of basal area and annual basal area increment. Aboveground live carbon stores over time are estimated from user-provided basal area and basal area increment estimates, but dead carbon (both above- and belowground) is not estimated, and as previously noted carbon stores over time are not the same as carbon flux. Forest harvest intensity (as basal area removed) and rotation interval are easy to modify, and the user can also specify the intensity of site preparation. THPGGEC does not quantify the impacts of natural disturbances on carbon pools and fluxes. THPGGEC is well suited to applications for which forest owners and managers have forest inventory information and want to estimate the carbon storage and emissions associated with forest management (including storage and emission associated with harvest, milling, and wood products). THPGGEC is not well suited to applications in which information is desired for forest carbon flux, dead carbon in forests, or the impacts of natural disturbances on forest carbon.

Group 4: Spreadsheet Forest Carbon Management Calculators without User Inventory Data (GTR-NE-343 and FORGATE). Compared with the calculators in group 3, calculators in group 4 do not require user-provided forest inventory and growth data, instead estimating carbon pools using a combination of national inventory data and growth-and-yield modeling. GTR-NE-343 and FORGATE are stand-alone spreadsheet tools that provide estimates of above- and belowground dead carbon pools, as well as estimates of carbon storage and emissions associated with milling, wood products, and disposal of wood products. Despite their similarities, GTR-NE-343 and FORGATE have very different constraints and ease/difficulty of use. GTR-NE-343 is parameterized for 51 major forest types across the continental United States (excluding Alaska), whereas FORGATE is only parameterized for major forest types in the State of Maine. In GTR-NE-343, the user needs to work through a number of "look-up" tables that are not dynamically linked to generate estimates of how harvests influence carbon pools in forests, wood products, and waste disposal. In contrast, the tables in FORGATE are linked, making it much easier for the user to calculate changes in forest sector carbon in response to management activities. FORGATE provides a set list of common silvicultural prescriptions that are much easier to apply than harvests in GTR-NE-343, in which any harvest activities besides complete harvest require additional calculations by the user. Both of these forest carbon calculators are suitable for applications for which forest owners and managers do not have detailed inventory data but want initial estimates of carbon storage and emissions associated with forest management activities (including storage and emissions associated with harvest, milling, and wood products).

Class 3, High System Complexity: Groups 5 and 6

This class represents the most complex forest carbon calculators, primarily characterized by high flexibility for which the user can simulate a wide range of harvest intensities, rotation lengths, and site preparation. All calculators in this class can operate at the stand level, as well as at larger spatial scales. Calculators in this class are also characterized by more complex representation of forest carbon dynamics, with quantification of above- and belowground carbon pools and fluxes. These calculators are more computationally intensive than classes 1 and 2, and they all operate as web-driven or desktop computer programs versus the spreadsheets and tables more common in other classes. Although similar with regard to representation of management complexity, there are important differences between them in input data, geographic extent, impacts of natural disturbances on forest carbon dynamics, and user interface, resulting in two groups and additional separation of the last group into two subgroups.

Group 5: Regional Carbon Decision-Support Tool (LMS). LMS is closely related to CR-FVS, in that both rely on the FVS (Dixon 2002) for growth-and-yield modeling to quantify carbon pools (LMS can optionally use the growth-and-yield model ORGANON [Hann 2006]). As with CR-FVS, the LMS user must provide detailed inventory data for the stand(s) to be analyzed, and both LMS and CR-FVS estimate the fate of carbon in the wood products stream. Unlike all other calculators in class 3, LMS does not quantify the impacts of natural disturbances on carbon pools and fluxes. When FVS is used, growth-and-yield modeling in LMS can be parameterized for major forest types and regions in the United States, but is restricted to forests of the Pacific Northwest when parameterized using ORGANON. LMS also provides outputs for a number of noncarbon management criteria, such as habitat suitability indices for northern spotted owl and economic revenue/cost analyses. LMS is well suited to applications as a decision-support tool, when detailed information is required about how management activities may have an impact on carbon pools and when these impacts need to be assessed against economic and other noncarbon management objectives.

Group 6A: Regional Carbon Decision-Discussion Tool (FSCC). Unlike other calculators in class 3, FSCC does not require the user to provide inventory data. Instead, FSCC is based on the process-based model LANDCARB (Harmon 2012) that simulates forest carbon dynamics in response to the primary factors that influence carbon dynamics (i.e., disturbance, climate, soils, and seed zones). We refer to the FSCC as a decision-discussion tool rather than as a decision-support tool, because its complex system representation (e.g., ecosystem processes and management activities) and relative ease of use from a website with a simple interface allows management scenarios to be quickly generated by a first-time user (Figure 3), yet the absence of user-provided inventory data precludes running scenarios for a specific stand(s) that are often needed in decision-support applications. The combination of high system representation and ease of use also makes FSCC useful as an educational tool about carbon dynamics in forest ecosystems and the wood products sector. The educational function is aided by accompanying tutorials designed as much to inform users about forest carbon dynamics as they are to teach users how to operate the calculator. FSCC is geographically limited to forests of the Oregon Cascades and to applications for which the user does not have forest inventory data, but wants to understand how different harvest, disturbance, and wood product uses influence carbon dynamics in the forest sector.

Group 6B: National Carbon Decision-Support Tools (CBM-CFS3 and CR-FVS). Both of these calculators are extensive decision-support tools that can model carbon dynamics in a wide range of forest types and geographic regions. They are both stand-alone computer programs with many user-adjustable settings. They require substantial time for a first-time user to generate outputs, although both have extensive documentation and training workshops. They both require the user to provide stand inventory data. Simulation of management activ-

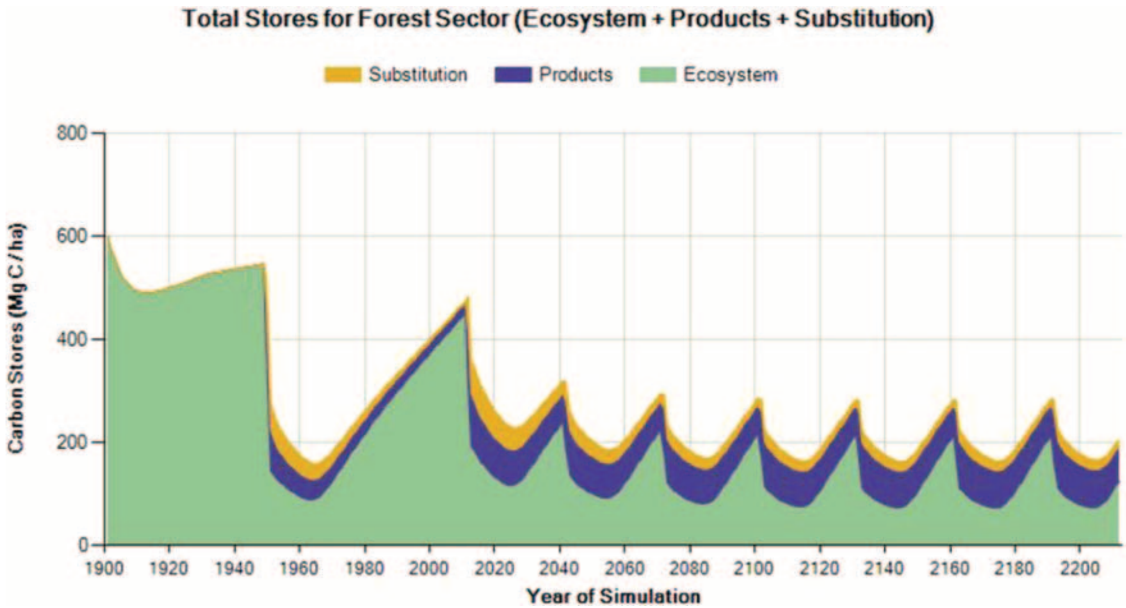

Figure 3. Example of carbon stores over time in a simulated forest stand in the western Oregon Cascades as generated by the FSCC. In this example, an old-growth forest was harvested in 1950, with a subsequent harvest in 2010 (60-year rotation), followed by harvests on a 30-year rotation.

ities and disturbance events such as wildfire are more sophisticated and flexible than those of any other calculators we reviewed. CBM-CFS3 tracks how much wood is transferred to the forest product sector by region, softwood, hardwood, and year of harvest, but the fate of carbon in harvested wood products is tracked in a separate model. In combination with other FVS extensions, it is possible in CR-FVS to assess carbon dynamics of management activities in relation to noncarbon management objectives such as economics and fire risk. CR-FVS and CBM-CFS3 are also unique in incorporating some climate change impacts on forest processes that in turn alter forest carbon dynamics (Crookston et al. 2010, Metsaranta et al. 2011). As the group name suggests, these carbon calculators are best suited to applications for which detailed inventory data are available, and users have the need and time to generate outputs to be used in a decision-support capacity.

Conclusions and Limitations of Current Forest Carbon Calculators

All carbon calculators are not created equal, nor do they have the same goals. They vary widely in forest system representation, data input requirements, and type of outputs. On one end of the spectrum are carbon calculators that represent forest carbon dynamics and management activities with a low degree of sophistication and complexity. These calculators are not well suited for examining stand-level carbon dynamics, but are easy to use, have broad geographic coverage, and require few data from the user. On the other end of the spectrum are fully developed decision-support tools that enable sophisticated and flexible examinations of forest carbon dynamics in response to management activities and some natural disturbance agents such as wildfire. However, these calculators are harder to run and often require more data from the user. The field of forest carbon calculators is rapidly evolving, and we expect many more to be developed in the near future to meet user needs and applications. In this context, we believe their potential usefulness could be improved through (1) incorporating the impacts of natural disturbances, (2) including impacts of climate change, (3) expanding the geographic extent of moderate-complexity calculators, and (4) developing education components such as tutorials to expand their use and improve carbon literacy.

Only the most complex calculators simulate the impacts of natural disturbances such as wildfire or insect outbreaks on forest carbon dynamics. Natural disturbance agents can result in significant reductions in forest carbon storage, even converting forests from sink to sources of atmospheric CO_2 (Dore et al. 2008, Kurz et al. 2008, Seidl and Blennow 2012). Furthermore, changes in forest structure and composition associated with management activities can strongly increase susceptibility to and severity of disturbances (Seidl et al. 2011). Alternatively, management activities can reduce susceptibility to disturbance agents. For example, thinning and prescribed fire are widely used to moderate stand-level fire behavior (for a review, see Agee and Skinner 2005). These management activities can have impacts on forest carbon emissions in landscapes prone to wildfires (Wiedinmyer and Hurteau 2010), whereas treatments that restore historical species composition and active fire regimes may stabilize future live-tree carbon stores (Earles et al. 2014). However, it is important to note that there is considerable uncertainty and debate about the impacts of forest management on carbon dynamics in fire-prone forests (Campbell et al. 2011, Hurteau et al. 2012, Campbell and Ager 2013, Restaino and Peterson 2013). This uncertainty is further complicated in the context of bioenergy production, for which utilization of residue from harvest operations may have favorable impacts on forest sector carbon dynamics versus traditional wood products such as pulp or lumber (Ter-Mikaelian et al. 2015). Even with this uncertainty, the absence of many disturbance types, as well as the lack of linkages between management, disturbance, and carbon is a major limitation in all but the most sophisticated forest carbon calculators.

The impacts of climate change on forest carbon dynamics are also largely absent from the carbon calculators we reviewed, with only limited incorporation into the most sophisticated calculators (CR-FVS and CBM-CFS3). Climate change may directly influence forest carbon dynamics by altering forest ecosystem processes such as growth, mortality, decomposition, and soil respiration (Allen et al. 2010, Latta et al. 2010, Giasson et al. 2013, Giardina et al. 2014), as well as altering the frequency and severity of disturbance agents such as wildfire, insect outbreaks, and windthrow (Westerling et al. 2006, Seidl et al. 2011, 2014). The effects of climate change on forest carbon dynamics and how management activities may interact with these effects, are highly uncertain. This uncertainty may preclude incorporation of many climate change impacts into forest carbon calculators, but as the projected effects of climate change on ecosystem processes become more certain, these processes should be incorporated into carbon calculators to assess future environmental conditions having an impact on forest carbon dynamics.

Three of the four calculators that are easy to use and moderately sophisticated (class 2) had very limited geographic extents. We recognize that many of these calculators were designed for specific local or regional applications and may not receive the funding or institutional support of larger-scale decision-support tools. However, these moderately sophisticated calculators fill an important application niche, enabling users to quickly make reasonable estimates of stand-level carbon dynamics in relation to common management activities, but the narrow geographic focus of these calculators greatly restricts their potential usefulness.

Finally, we found that few of the carbon calculators included tutorials and additional information designed to teach users about carbon dynamics in the forest sector. It could be argued that forest carbon calculators are designed for use by people who already have a certain level of understanding about forest sector carbon dynamics, and so documentation should be focused on user guides rather than on broader education. However, without basic training or knowledge of forest sector carbon dynamics, users may not be able to appropriately parameterize carbon calculators, critically evaluate outputs, or compare difference management scenarios from a carbon dynamics perspective. Furthermore, free and easy-to-use carbon calculators are an excellent platform for inclusion of tutorials and information that improve the carbon literacy of users. We suggest that future development of educational content in carbon calculators with specific characteristics (i.e., web-driven, easy-to-use, and with moderate-to-high system representation) would greatly enhance the education component of carbon calculators and improve the carbon literacy of users.

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