Chapter 5 Quantifying Greenhouse Gas Sources and Sinks in Managed Forest Systems

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Table of Contents

List of Appendixes

List of Tables

List of Figures

Acronyms, Chemical Formulae, and Units

AFOLU	agriculture, forestry, and other land use
ATLAS	Aggregate Timberland Assessment
C	carbon
CBM-CFS3	Carbon Budget Model of the Canadian Forest Sector
CCF	hundred cubic feet
CCT	Carbon Calculation Tool
CH_4	methane
cm	centimeter
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
COLE	Carbon OnLine Estimator
dbh	diameter at breast height
DDW	down dead wood (otherwise termed downed woody material)
DF	displacement factor
FFE	Fire and Fuels Extension
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FOFEM	First Order Fire Effects Model
FORCARB2	FORest CARBon Budget Model
FOROM	Forest Resource Outlook Model
FVS	Forest Vegetation Simulator
g	gram
GHG	greenhouse gas
GIS	geographic information system
GPS	Global Positioning System
GWP	global warming potential
ha	hectare
hp	horsepower
HWP	harvested wood product
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	kilogram
LCA	life cycle assessment
LEARN	Land Emissions and Removals Navigator
m	meter
MBF	thousand board feet
Mg	megagram (metric ton or 1,000,000 grams)
MRV Toolkit	Measurement Reporting and Verification Toolkit
Mt	million metric tons
N_2O	nitrous oxide
NSVB	national scale volume and biomass
PEF	pollutant emission factor
RPA	Resources Planning Act
SOC	soil organic carbon

SQL	structured query language
SUNY	State University of New York
SWDS	solid waste disposal sites
Tg	teragram (million metric tons or 1,000,000,000,000 grams)
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound
WARM	Waste Reduction Model

5. Quantifying Greenhouse Gas Sources and Sinks in Managed Forest Systems

This chapter provides methodologies and guidance on estimating greenhouse gas (GHG) emissions or carbon removals (i.e., sequestration) associated with entity-level activities of the forestry sector:

- Section 5.1 provides an overview of management practices and resulting GHG emissions or carbon removals, including silviculture practices and treatments, harvested wood products (HWPs), urban forest management, and wildfire and prescribed fire.[1] It also discusses system boundaries and temporal scale, the selected methods/models, and sources of data.
- Section 5.2 provides the methods for estimating carbon stocks and carbon stock change from managed forest systems. Note that—because forest operations are often integrated and planned over more space and time than other operations covered in this guidance—many entity-scale GHG estimations will need to use a number of these methods.

This chapter has three appendixes, as well as an accompanying Excel workbook:

- Appendix 5-A provides an overview of silvicultural practices, HWPs, urban forest management, and natural disturbances, including a general background for forestry management activities and details on how to use online tools.
- Appendix 5-B provides the rationale and technical documentation for the chosen methods.
- Appendix 5-C summarizes the known research gaps that inform these chosen methods as well as provides the basis for future development of methods.

The Excel workbook facilitates quantification approaches for silvicultural practices and improved forest management (section 5.2.1), HWPs (section 5.2.2), and wildfire and prescribed fire activities (section 5.2.3). It provides the resulting GHG estimations or carbon removals with user-defined inputs. These results are divided along sector boundaries to better agree with Intergovernmental Panel on Climate Change (IPCC) guidance. See table 5-5, in section 5.1, for a brief guide to the Excel workbook's structure.

5.1 Overview

The chapter is designed to be accessible to a diversity of users with a wide range of technical capacities and data availability. It also recognizes the continuum of specific goals for forest management activities meant to enhance carbon stocks or lower emissions.

5.1.1 Description of Sector

Forests are the largest terrestrial carbon sink in the world, taking in carbon dioxide (CO_2) and storing it as carbon in soils and woody plants (Pan et al., 2011) and HWP. In the United States, forests, urban trees, and wood products collectively offset total annual CO_2 emissions by 10–15 percent (USDA Forest Service, 2021), although this varies by State and region. In the 2021 annual GHG inventory reported by the U.S. Department of Agriculture (USDA) and the U.S. Environmental Protection Agency (EPA), forests sequestered a net total 593 million metric tons (Mt) of CO_2 per year on 281 million hectares (ha) of forest land, making this the main land category sequestering

[1] In this chapter, the terms "prescribed burn" and "prescribed fire" are applied synonymously when referring to fire that is intentionally ignited to meet management objectives.

carbon. Urban trees in settlement areas sequestered an additional net 138 Mt. A further 103 Mt CO_2 (new product storage and emissions) were added in 2021 to the pool of carbon stored in wood products. Collectively this represents an annual net 760 Mt of carbon dioxide equivalents (CO_2-eq) sequestered in 2021 (Domke et al., 2023).

These estimates have remained relatively consistent over the past two decades, despite increases in forest disturbances such as pests and wildfire, continued encroachment of settlements on forest areas, and demand for wood products (Oswalt et al., 2019). There are some indications that without additional investments in forests (both forest areas and settlement tree cover) these annual additions to the stored carbon pool will decline toward net-zero sequestration in the forest sector as available land becomes limited for afforestation, more land converts to development, and climate-induced disturbances reduce existing carbon stocks (Domke and Murray, 2021; Oswalt et al., 2019).

Forest management activities can substantially influence the amount of carbon stored in a forest, as well as what is available for use as wood products or bioenergy. The specific operations involved also affect the size of the carbon benefit that can be gained. Although operations such as tree harvesting, planting, fertilization, and trucking also produce GHG emissions from the fossil fuel used to carry out these activities (Ingerson, 2011), such emissions are not the focus of this chapter.

A range of forestry activities can be considered in projects that attempt to store atmospheric CO_2 as carbon in wood or avoid anticipated emissions. These include establishing new forests, planting trees on agricultural or urban land (i.e., agroforestry or urban arboriculture), avoiding forest clearing, avoiding wildfire emissions, and a range of silvicultural treatments/practices such as extended rotation lengths and uneven-aged silvicultural systems that enhance carbon stocks in managed forests and/or increase the resilience of these stocks to future global climate change effects. Forest management may be very effective at increasing the rate of biomass accumulation in commercial tree species. (See table 5A-2 in appendix 5-A for an extended list of the range of forest management activities among commercial even-aged plantations.) Forestry activities can also have effects on forest soils, woody debris, and the amount of carbon in wood products. These interventions often result in both emissions and removals of carbon.

Key concepts where harvesting occurs include:

- Climate benefits from harvesting under any rotation scenario have a much higher likelihood of realization if the carbon contained in the harvested stand is transferred into wood products. The exception may be in cases where it can be demonstrated that harvesting is effective in avoiding future emissions from disturbances such as fire, drought, and pests. In these cases, utilizing harvested biomass as wood products can increase the climate benefit.
- Where harvests are undertaken, postharvest land use is an important factor. Long-term climate benefits have a higher probability of achievement if harvests are responsibly conducted (e.g., maintain soil health and ensure tree regeneration) and postharvest land use continues as forest (through either natural regeneration or active planting of seedlings).

5.1.2 Resulting GHG Emissions

Through photosynthesis, green vegetation pulls CO_2 from the atmosphere, separates the carbon, and releases oxygen. Some of that carbon is returned to the atmosphere as $CO_2$when the plant uses carbon to produce energy while a large proportion is stored in plant tissues. This plant tissue, otherwise known as biomass, stores the carbon until its dead matter decomposes or combustion releases it as CO_2 to the atmosphere.

The carbon stock in forests increases when the amount of carbon withdrawn from the atmosphere through the growth of trees and plants (including lateral transfer to other pools such as dead wood) exceeds the release of carbon to the atmosphere. This is called "net sequestration" or "net carbon removal." U.S. forests as a whole have been in this state for over 100 years as they regrew in extent and size following extensive land clearing in the 1800s (Birdsey et al., 2006).

Forests may also become sources of CO_2 when disturbances, whether natural or human-caused, exceed the amount of growth in the forest. During and after these events—such as outbreaks of insects or disease, hurricanes, droughts, and wildfires or timber harvest—the rate of carbon emissions exceeds sequestration and net GHGs are added to the atmosphere.

CO_2 is always included in estimates of GHG flux from forest management activities. When forest ecosystems exchange other GHGs with relatively higher global warming potential (GWP), such as nitrous oxide (N_2O) and methane (CH_4), those gases are especially important to include if possible (see table 5-1). (See chapter 2 for more information on GWP.)

Table 5-1. GHGs Associated With Forest Management Activities

GHG	Driver of Flux in Forest Ecosystems	Associated Forest Management Activity
CO_2	Photosynthesis and decay/combustion of biomass.	All
N_2O	▪ Emitted from soils under wet conditions or after nitrogen fertilization. ▪ Released when biomass is burned.	▪ Emissions from fertilizer application ▪ Wildfire/prescribed fire
CH_4	▪ Often absorbed by the microbial community in forest soils but may also be emitted by wetland forest soils. ▪ Emitted when biomass is burned, particularly smoldering combustion of large-diameter woody fuels and ground fuels (Sommers et al., 2014).	Wildfire/prescribed fire

5.1.3 Carbon Pools

Carbon makes up about 50 percent of the dry weight of forest vegetation, also known as "biomass" (IPCC, 2006), though that proportion can vary depending on species and ecosystem type (Doraisami et al., 2022). Forest carbon accounting therefore primarily relies on estimating how much biomass and organic matter from biomass is in the system, including wood products. Forest biomass is delineated into discrete "carbon pools" (see figure 5-1 and table 5-2).

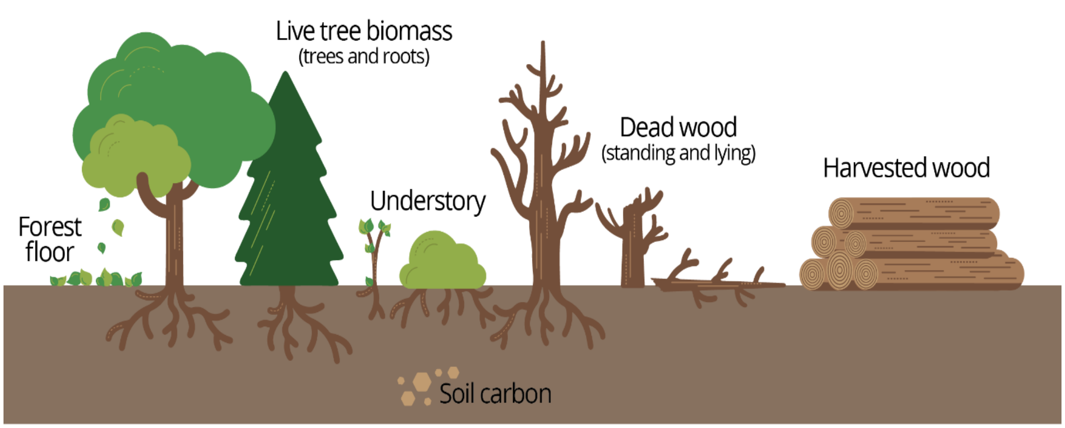


Figure 5-1. Forest Carbon Pools

Box 5-1. Land-Use Change vs. Land-Cover Change

The terms "land use" and "land cover" are often confused or used interchangeably, but there is an important distinction in the context of forest carbon accounting dynamics.

Land cover: The observed biophysical cover on the earth's surface (Di Gregorio and Jansen, 2005). In the forestry context, forest land cover may decrease over a monitoring period as a result of disturbances like fire, disease, and harvest (Nelson et al., 2020). This tree cover loss does not equal deforestation because trees will often regrow after those disturbances. For example, forest management practices and harvest cycles often result in temporary land cover changes. Whether through replanting or natural regeneration, the forest cover returns over time.

Land use: The human-designated purpose or intent of the land regardless of the vegetative cover. Changes in land use reflect a more permanent transition to another ecosystem type. "Deforestation" specifically refers to instances where the land use (and often land cover) is permanently changed, i.e., where land transitions from forest to another land use. In the United States, the largest driver of land-use change is development for commercial and residential purposes (Nelson et al., 2020).

Carbon pools can be grouped in several different ways. This guidance uses a standard set of carbon pool definitions—those applied in the Forest Inventory and Analysis (FIA) program's national inventory—that correspond to available lookup tables (Smith et al., 2006; Hoover et al., 2021). However, definitions and boundaries around pools can vary according to specific carbon estimation procedures/capabilities and reporting needs.

The biomass in these pools is generally not measured directly (i.e., through forest biomass sampling for laboratory determination of carbon content); instead, it is estimated indirectly using measurements from standard forest inventories and modeled associations.

It is best practice to identify the pools that will be accounted for at the beginning of the quantification effort. All relevant pools should be included, unless it can be shown that a pool would not have stock losses or emissions or anticipated carbon stock changes can be considered negligible or *de minimis* (see box 5-2).

Table 5-2. Summary of Carbon Pools

Forest Carbon Pools	Description
Live trees	Large woody perennial plants, capable of reaching at least 15 feet (4.6 meters) in height, with a diameter at breast height (dbh) or at root collar (if multi-stemmed woodland species) greater than 1 inch (2.5 centimeters). Includes the carbon mass in roots (i.e., live belowground biomass) with diameters greater than 0.08 inches (2 millimeters), stems, branches, and foliage. The per-tree carbon estimates are a function of tree species, diameter, height, and volume of wood. Trees less than 5 inches (12.7 centimeters) dbh are often sampled differently than those that are 5 inches (12.7 centimeters) or more.
Understory	Biomass of undergrowth plants in a forest, including woody shrubs and trees less than 1 inch (2.5 centimeters) dbh. Generally, a minor component of biomass or the live plant component.

Forest Carbon Pools	Description
Standing dead	Dead trees of at least 1 inch (2.5 centimeters) dbh—including carbon mass of coarse roots, stems, and branches—that have not yet fallen and do not lean more than 45 degrees from vertical (Burrill et al., 2021).[a] Includes coarse nonliving roots more than 0.08 inches (2 millimeters) in diameter.
Down dead wood (DDW), also known as coarse woody debris	All nonliving woody biomass with a diameter of at least 3 inches (7.6 centimeters) at transect intersection, lying on the ground. This pool also includes: ▪ Debris piles, usually from past logging ▪ Previously standing dead trees that have lost enough height or volume or lean more than 45 degrees from vertical so they do not qualify as standing dead ▪ Stumps with coarse roots (as previously defined) ▪ Nonliving vegetation that otherwise would fall under the definition of "understory" ▪ Coarse roots associated with fallen trees
Forest floor	The litter, fulvic, and humic layers, and all fine woody debris with a diameter less than 3 inches (7.6 centimeters) at transect intersection, lying on the ground above the mineral soil.
Forest soil organic carbon (SOC)	All organic material in soil to a depth of generally 3.3 feet (1 meter), including the fine roots—e.g., roots less than 0.08 inches (2 millimeters) in diameter—of the live and standing dead tree pools, but excluding the coarse roots of the aboveground and belowground live and dead biomass.
Products in use	Wood removed from the forest ecosystem and processed into products, not including logging debris (slash) left in the forest after harvesting.
HWPs in solid waste disposal sites (SWDS)	Wood products discarded into SWDS. Most of the carbon from long-lived or solid wood products remains stored for time periods exceeding a century, whereas most paper products are subject to decay over much shorter periods.

[a] The minimum diameter of standing dead trees may be increased (5 inches, or 12.7 centimeters, dbh) to accommodate past sampling protocols for estimation of change.

Box 5-2. The *De Minimis* Assumption

It is best practice to include all pools in efforts to quantify GHG flux from forest management activities, unless one can show that a pool's stock changes are small and do not significantly contribute to the total carbon stocks, or that a pool would not have stock losses or emissions. This is called the *de minimis* assumption, made when the change in the pool in question makes up an insignificant proportion of the total anticipated change in forest-related emissions within the accounting period. For this guidance, the *de minimis* threshold is 10 percent. For instance, in a reforestation activity where it may be difficult, time-consuming, or costly to estimate soil carbon change, and the soil carbon change is assumed to be *de minimis* in magnitude, it may be omitted from the quantification of total flux. Or, if it can be demonstrated that the soil pool will be accumulating carbon, the landowner may choose not to count that pool and thus be conservative about (i.e., underestimate) the sequestration potential of the project. This is an example of balancing principles of completeness and cost-effectiveness. Generally speaking, nontree vegetation is not a significant biomass component in mature forests, and the deadwood pool is typically not a significant part of carbon stocks in reforestation; the stock changes associated with such pools therefore could be considered *de minimis* (Pearson et al., 2005).

Products in use and products in solid waste disposal system pools are included in the forest carbon pool because they enable complete accounting of carbon as it cycles through creation to emission: captured in forest biomass through photosynthesis → potentially harvested → burned or decaying at various rates (depending on the biomass's fate), with some of the carbon ultimately returning to the atmosphere, but much of it stored indefinitely in landfills. IPCC defines these stages as forest carbon, carbon stored in products in use, and carbon stored in HWPs in solid waste disposal sites (SWDS) (such as landfills).

Table 5-3 provides considerations around including particular pools and GHGs in quantifying GHG flux from forest management activities.

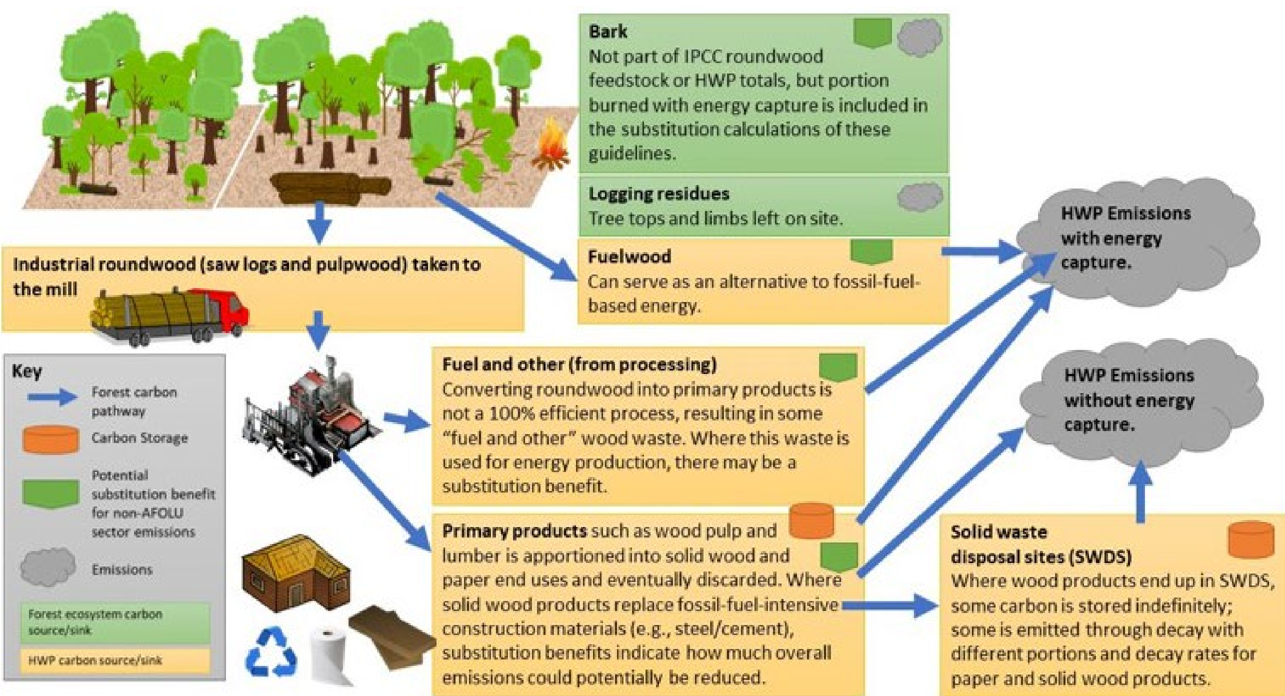
Table 5-3. Pools and Gases Relevant in Quantifying GHG Flux for Forest Management

Pools and Gases	Considerations
Live trees	This is a major carbon pool and relevant to quantification.
Understory	It is best practice to include understory carbon for completeness, but it is rarely significant for reforestation activities. However, in terms of forest ecosystem dynamics, understory attributes can greatly affect tree regeneration and survival rates.
Standing dead	Depending on stand age and disturbance history, may be relevant to quantification. For completeness, it is best practice to include. It is expected that, if tree mortality starts to increase due to global change, this pool will become more important in determining flows of forest carbon.
DDW, also known as coarse woody debris	Depending on stand age and disturbance history, may be relevant to quantification. It is best practice to include DDW for completeness, but it is rarely significant for reforestation activities. In the case of wildland fire, deadwood and forest floor pools are the largest immediate sources of emissions.
Forest floor	For completeness, it is best practice to include. For reforestation activities, this carbon pool is rarely significant. In the case of wildland fire, deadwood and forest floor pools are the largest immediate sources of emissions.
Forest SOC	For most North American forest types, soil carbon accumulation may be omitted: it is likely to change at a slow rate and is an expensive pool to measure. Accruals within the first 25 years may not represent a significant proportion of carbon stocks, and therefore could be considered *de minimis* in many cases. Exceptional cases, such as wet high-carbon peatland forests, may need more consideration.
Products in use	If feasible, and if forest harvesting takes place, products in use are relevant to quantification. For completeness, it is best practice to include because a significant proportion of forest carbon stocks can be stored in HWPs.
HWPs in SWDS	If feasible, and if forest harvesting takes place, HWPs in SWDS are relevant to quantification. For completeness, it is best practice to include because a significant proportion of products in use are either temporarily or permanently stored in SWDS.
CO_2	This GHG is very relevant to quantification.
CH_4	Depending on the forest management activity, may be relevant to quantification. The land-use sector accounting does not typically include CH_4 emissions from reforestation, extended rotation, and avoided deforestation activities. However, they may be important for addressing impacts of wildfire or prescribed fire (covered in section 5.2.2).
N_2O	Depending on the forest management activity, may be relevant to quantification. GHG impacts from reforestation, extended rotation, and avoided deforestation activities within land-use sector accounting do not typically include N_2O emissions, especially if the site is not fertilized. However, N_2O emissions may be important to consider in addressing the impacts of wildfire or prescribed fire (covered in section 5.2.2).

5.1.4 Management Interactions

Forest management activities can cause carbon to move between different carbon pools in the forest ecosystem, into HWPs, and to/from the atmosphere. They may influence the amount of total carbon stored in a forest ecosystem, as well as the amount of carbon that is stored in HWPs or SWDS when transferred out of the forest ecosystem pools.

Some forest management activities will result in accelerated loss of forest carbon through soil disturbance (i.e., through accelerated oxidation of soil organic matter), or when prescribed burning releases CO_2 and other GHGs. Forest management may also require the use of equipment that is powered by fossil fuels. For example, when a site is cleared, carbon may move from the live trees into harvested wood, and some of the wood carbon may also be released into the atmosphere via decay or burning of the harvested wood (see figure 5-2). When a site is planted, growing trees' carbon increases as they remove CO_2 from the atmosphere and store it in their living biomass. In some cases, a forest management practice emits carbon but causes a long-term improvement to gross CO_2 removal via forest growth and resilience, resulting in more net carbon stored in the forest through time. Some fuel management activities, for instance, may lower carbon stocks by removing fuels (biomass) from the landscape over short periods but create a longer term carbon benefit by enhancing forest health and lowering emissions associated with avoiding potentially severe fire in the future. Accounting for the total net flux (both emissions and carbon removals) and the relative timing of these changes is an important part of ensuring completeness in quantification. The net carbon results of any activity will be the net sum of all the individual effects (i.e., emissions and carbon removals) across different carbon pools and time scales.



Emissions featured in this figure are GHGs and do not reflect other air pollutants. AFOLU = agriculture, forestry, and other land use; HWP = harvested wood product; IPCC: Intergovernmental Panel on Climate Change (United Nations); SWDS = solid waste disposal sites

Figure 5-2. Diagram of Carbon Flux: Pathways Forest Carbon Can Take to the Atmosphere

Natural disturbances such as drought, wind or flood events, wildfire, insects, and disease convert live vegetation to dead, altering carbon dynamics. They may reduce carbon captured by photosynthesis in the short run due to reduced vegetative cover and increase emissions from decomposition of dead vegetation.

In addition, there may be interactions between biological and physical processes that are affected by forest management treatments or natural disturbances—for example, changes in albedo (reflectivity) during forest regeneration after wildfires, as discussed in appendix 5-C. Applied research in this field is in the early stages, so this guidance does not discuss such interactions.

5.1.5 Accounting Boundaries

Clearly defining and delineating boundaries helps avoid double-counting, imbues transparency around what estimates do or do not include, and helps ensure efforts to measure and monitor emissions or carbon removals can be undertaken in a comparable way over time.

The following sections describe the types of boundaries to consider in forestry entity-scale reporting.

5.1.5.1 Spatial Boundaries

The spatial boundary is the geographic area in which project activities take place. For this chapter, this is defined as the extent of the landowner's property. However, these guidelines recognize the complexities within ownership arrangements across forested lands and may also be applicable to communal lands or other complex multi-landowner entities governed by a documentable, coordinated management regime. The key consideration is capturing all the interrelated land use decisions made by the managing entity to avoid missing GHG emissions/carbon removals from management activities in the accounting (to the extent possible). Such exclusions would give misleading estimates of the impact of an entity's decisions. Explicit guidance on delineating spatial boundaries is offered in sections 5.2.1, 5.2.2, 5.2.3, and 5.2.4 below.

The carbon pools that fall within the sector boundaries are described in table 5-3. Where harvesting occurs, some of the carbon pools that should be accounted for are located outside the landowner's property as HWPs are transported to the mill and become "products in use" or enter SWDS (see figure 5-2).

Stratification is an important concept in delineating land areas appropriately for the purpose of monitoring and assessment. Forests within an entity can be highly variable in composition and structure and subject to a range of management activities, which all may affect the amount of carbon stored and released over time. Delineating and grouping land into homogenous units—"strata"—can help reduce sampling effort, increase the accuracy and precision of accounting by reducing field data variability, and make it possible to apply different quantification approaches/assumptions based on management practices or biophysical conditions.

Land could be partitioned, for example, by forest type, productivity class, management intensity, and/or average tree age for even-aged stands. Forest strata will often, but not necessarily, be contiguous. The landowner can choose the stratification scheme to employ. A good stratification approach can increase the accuracy and precision of carbon estimates and potentially lower the extent of data collection needs and associated resources.

For instance, a reestablishment project may undertake two distinct interventions within the boundaries of the landholding, one for a commercial plantation and the other for natural regeneration. These areas would be stratified into two stands, as they have different carbon sequestration rates. If the project or property is to be a single forest cover, such as a natural regeneration forest or a plantation forest, the project site can be a single stratum, but other factors may be important, such as land slope or soil conditions, that may significantly impact the carbon outcomes for the same activity. Box 5-7 in section 5.2.1.1 provides resources on designing sample-based inventories and stratification.

Note that many mapped products or methodologies that are available at the regional and national scale can, using relatively simple GIS operations, predict carbon (or biomass) over a specified area, including at the individual entity level (Riley et al., 2021; Ohmann and Gregory, 2002). While these mapped products may be very useful for stratification or regional planning, their carbon predictions in small areas may be highly uncertain. They may not be appropriate sources of direct estimates of carbon, or carbon change, at the entity level.

5.1.5.2 System Boundaries

System boundaries reflect what activities will be accounted for, what the relevant GHGs are, and what carbon pools will be included. In other words, they pertain to defining the types of emissions considered and where they originate. The carbon pools and GHGs that fall within the sector boundaries are described in table 5-3.

Estimation methods presented in this section are for forest management activities. However, these activities may interact with animal agriculture or croplands and grazing lands. Users should refer to other chapters for relevant guidance on estimating GHGs from those sources to ensure complete accounting that avoids double-counting. In addition, any land-use transitions that occur within a property must be accounted for so that apparent changes in carbon stocks or fluxes are “real,” not the result of an unrecorded transfer from one sector to another.

5.1.5.3 Sector Boundaries

This guidance primarily is limited to GHG accounting within the agriculture, forestry, and other land use (AFOLU) sector, but forest management activities may induce GHG impacts across multiple sectors. (See chapter 2 for more details on sectors.) The majority of methods in this guidance do not represent life cycle assessment (LCA) approaches. The exception is the methods for HWPs: because HWPs play a significant role in the overall GHG impact of forest management activities, understanding the emissions impact of processing and transporting them can inform a more complete picture. Accordingly, section 5.2.1 does expand into an LCA approach for HWPs. LCAs are typically used to evaluate GHG emissions for a specific material or product. They tend to span sectoral boundaries; businesses use them to evaluate GHG emissions from raw material extraction, processing, manufacturing, and transportation through disposal of a product, material, or service.[2]

The machinery employed to harvest, transport, and process timber derives energy from the combustion of fossil fuels. Energy is a separate emissions sector, and therefore these guidelines do not address fossil fuel emissions from silvicultural practices, with a few exceptions:

- For a more holistic understanding of the GHG impact of forest management activities, estimates of potential emission reductions from wood product substitution are offered in the HWP methodologies described in section 5.2.1, which offers a means to quantify the fossil fuels emissions through a cradle-to-gate LCA (from where a tree was grown to leaving

[2] See https://epa.gov/sites/default/files/2016-03/documents/life-cycle-ghg-accounting-versus-ghg-emission-inventories10-28-10.pdf for more information on GHG emission inventories versus LCAs.

the forest boundary when harvested and transported off site). Where sectoral boundaries are breached to offer a more complete estimate of GHG fluxes from forest management activities, these estimates will be calculated and presented separately in the accompanying Excel workbook for "Level 1" estimates with ample justification and guidance on application.

- This chapter references i-Tree software tools for quantifying GHG impact estimation in the urban forest context. Some of these do offer means to quantify emissions from forest maintenance, focusing on fossil fuel use in machinery.

Fertilizers applied as part of forest management practices also need energy to produce and transport, but that energy may be offset by the additional growth in biomass they are designed to trigger (see box 5-3). As stated in chapter 2, this guidance limits GHG quantification methods to the AFOLU sector, with limited exceptions.

Box 5-3. Emissions from Fertilizer Application

Fertilizers influence net GHG flux in a holistic sense: their production requires energy; the use of nitrogen-based fertilizer release GHGs such as N_2O after application; and they may increase tree growth and sequestration rates. These interactions are complex and take place across multiple sectors. Research in western Canadian forests showed soil GHG fluxes were neutral following fertilization (Basiliko et al., 2009). In an analysis of fertilization of pine plantations in the southeastern United States, Albaugh et al. (2012) found carbon sequestration in forest growth far exceeded the emissions associated with fertilizer production, transport, and application (8.70 Tg/year CO_2 sequestration vs. 0.36 Tg/year emissions). Thus, forest fertilization when applied appropriately can dramatically increase carbon sequestration. Given these complexities, emissions from fertilizer application within forest management activities are not included in this chapter, with the exception of emission factors in the "Level 1: LCA Method for Quantifying HWP GHG Emissions" section (within section 5.2.2.1).

Products from forest management practices are also linked to other sectors of the economy; for example, forest managers' decisions can dramatically affect GHG emissions in energy production, construction, or agriculture. In the case of wood product substitution (covered in more detail in section 5.2.1), harvested wood can be used in construction or manufacturing to reduce the need for materials with a larger GHG footprint, like plastic, steel, and concrete.

Although these external impacts are often context-specific, require substantial assumptions, and are difficult to specifically quantify, it is important to note that these outside GHG impacts can at times be as large as or larger than the GHG changes within the entity boundaries. Similarly, new activities or economic shifts outside the forestry sector can have an influence inside the forestry sector. Even where these impacts cannot be quantified according to this guidance, they should be considered to the extent possible when evaluating the desirability of a management action for GHG mitigation to avoid misleading estimates of GHG performance and perverse impacts.

5.1.5.4 Temporal Boundaries

GHG accounting for forest management activities presents challenges related to time scales that may not occur in other sectors or agricultural activities. Agricultural products often mature in an annual cycle, but forestry operations occur over multiple years and decades. Furthermore, while annual estimation and reporting are sometimes required, annual measurements of forest carbon pools are not generally economically feasible, nor are changes in carbon stocks generally detectable within acceptable error levels on an annual basis. This necessitates the use of forward-looking models and projections to assess the GHG consequences of management practices and evaluate the possible benefits of a change in management practices over decadal time scales. These forward-looking projections should consider future management activities that can be reasonably foreseen due to management plans, landowner intent, or reasonably predictable consequences of management decisions.

GHG sequestration or emissions from forestry practices are also not necessarily consistent over time. For example, a newly established forest will take up carbon slowly at first, then pass into a period of relatively rapid carbon accumulation. The carbon uptake rate will then typically decline, sometimes leveling off as growth is balanced with mortality in many older forests. This is why carbon sequestration rates (i.e., carbon removal factors) for a single forest type are sometimes grouped into age classes to more accurately portray the rate at which they remove carbon from the atmosphere through time (see section 5-A.1.2 for a more complete description of "removal factors"). Because older forests tend to have lower rates of active carbon sequestration but higher overall carbon stocks, it may not be possible to maximize carbon stocks and sequestration simultaneously.

Furthermore, more resilient forests may have less carbon stored in them than overstocked or unhealthy forests. While standing live tree biomass may not increase substantially, carbon may continue to flow into other forest carbon pools until the forest is disturbed by harvests or natural means. This guidance does not attempt to determine the appropriate level of carbon for a project area or forest, but rather allow landowners to understand the GHG implications of their management activities.

Collectively, the diversity of forest ecosystems across the United States develops at varying rates, depending on a host of variables including species composition, ecological conditions and climate, management and disturbance history, and management practices. No set temporal scale for accounting is therefore offered in this chapter, though estimates for GHG emissions and removal produced by the simple Level 1 approach supported by the accompanying Excel workbook in this guidance apply a 50-year boundary for GHG emissions and carbon removals from silvicultural practices (on the forest ecosystem side) and a 100-year boundary for the carbon stored in HWPs (see section 5.1.6 for a summary of the selected methods and descriptions of "Levels"). Due to large uncertainties about long-term consequences of fire as well as future management activities and disturbances (e.g., future fire), the temporal boundaries used in the wildland fire emission estimates in this guidance are limited to immediate fire effects. It is acknowledged that postfire vegetation regrowth represents a future carbon sink, and the current omission of this component under the Level 1 approach renders an incomplete account of the impact of fire. Future versions of this guidance are expected to include postfire vegetation regrowth under the Level 1 approach.

The variability of forest GHG dynamics over time also depends on the characteristics of the forest ecosystem and the products produced from it. For example, a forest fuel reduction project may create GHG emissions by releasing stored carbon in the near term yet reduce the risk of future unplanned emissions for the entity or the larger landscape in which it is located in the medium to long term due to reductions in high-intensity wildfire or other disturbance. Materials created by the fuel reduction project may also continue to store portions of the forest carbon for years or decades as wood products and eventually in landfills (SWDS).[3]

[3] Though landfills may also be a significant source methane emissions, depending on design and management practices, offsetting any storage benefit.

Box 5-4. The Stochastic Nature of Unplanned Disturbances

Further complicating GHG accounting within the forestry context is the stochastic (random) nature of unplanned disturbance events over the lifetime of a management practice. For example, a forest stand with an approximately 50-year fire return interval may not experience any fire disturbance for 80 years, but then experience a second fire at only a 15-year interval. The net GHG implications over time of a management intervention that creates near-term emissions will depend heavily on this inherent variability. Therefore, it is very challenging to quantify the future unplanned emissions of a forest entity without either making largely unknowable assumptions about the future or using probability modeling such as Monte Carlo simulation approaches. This is further complicated by climatic changes, policy interventions, technological advances, and other factors that are continuously changing the probabilities and future risks of GHG emissions from these systems.

There are no "correct" answers to balancing such near-term vs. longer term fluxes, and judgments of the desirability of these management actions will depend heavily on assumptions about future disturbance/emission risks, entity values and preferences, and other emissions occurring outside the entity boundaries in other sectors.

5.1.6 Summary of Selected Methods

As shown in table 5-4, this chapter describes methods for estimating emissions or carbon removal from silvicultural practices and improved forest management, carbon storage and emissions and LCA-quantified substitution impacts from HWPs, emissions from wildfire and prescribed fire, and GHG flux from urban forest management. The specific method to choose depends in part on circumstances unique to each entity, but even more on the intended use of the estimate and the resources available to quantify and/or monitor emissions.

At the entity scale, repeated annual remeasurements are not practical in most cases, nor are the annual changes in carbon stocks significant enough to justify annual remeasurements. Instead, data from published studies or reputable sources or projection models (e.g., lookup tables) can be used to account for carbon stock losses or gains (Janowiak et al., 2017). Appendix 5-A.1 provides general background on activity data (including discussion of stock-change and gain–loss) and a summary of the type of estimates within these methods.

This chapter offers options, called "Levels," of approaches to generating estimates for each forest management activity. The methodologies and underlying data for each Level confer a particular level of accuracy and data accessibility, as well as cost. Generally, where higher accessibility is achieved, accuracy is sacrificed. Nevertheless, each approach offered is considered scientifically sound and grounded in fully credible data and methodologies. The Level 1 approaches offered in this chapter can be considered comparable to an IPCC Tier 2 approach, applying region-specific data and reflecting an intermediate level of methodological complexity. Levels 2 and 3 could be considered congruent with IPCC Tier 3. While not all of the forest management activities included in this chapter offer all three Levels, at least one Level 1 option is proposed for each activity. Users may use different Levels for the different forest carbon pools (e.g., Level 1 for DDW but Level 3 for standing live trees), but this variability does not exist in the accompanying Excel workbook. (See table 5-5 for more information on the Excel workbook.)

- **Level 1** approaches are most accessible and are envisioned to enable generalized estimates of GHG flux from a limited set of forest management activities requiring only basic user inputs. Applying the ''gain–loss" approach to GHG inventories (see appendix 5-A.1.2), users need minimal information to estimate current carbon stocks, associated GHG flux (i.e., combining area of intervention with relevant emission or removal factors), and potential impacts from selected forest management activities. For forest management activities included in the accompanying Excel workbook, users enter basic information such as the location and land area (acres) of the area in question; the tool will draw appropriate data from built-in data (i.e., "lookup tables") to produce estimates. This workbook is meant to facilitate the estimation of GHG flux for a broad range of users and is an initial demonstration of often complex calculations across system boundaries (ecosystem to HWP to decay/combustion). As described in chapter 2, users can either calculate a "basic projection" or estimate the impact of a management change. A basic projection offers a prediction of the carbon flux of a forest parcel that is maintained (similar to a baseline, status quo, or business as usual scenario). Estimated impacts from a management change require a comparison between the baseline as well as the management intervention scenarios. The difference between these scenarios represents the net impact of adopting the management practice.

- **Level 2** approaches generally apply the same methodologies as offered in Level 1, but require more proficiency in forest carbon accounting and data access/knowledge. Users can choose locally relevant emission factors or removal factors to apply rather than the regional defaults used in Level 1 estimates. For example, inventory data for Level 2 or Level 3 approaches might be obtained from extension foresters, or for Tribal lands from the Bureau of Indian Affairs' Continuous Forest Inventory (obtained through the Bureau's Branch of Forest Resources Planning).
- **Level 3** approaches involve direct measurements and/or more complex modeling approaches that represent a more advanced user's needs and capacities and a higher level of certainty in forest carbon accounting. For example, the FVS (Forest Vegetation Simulator) modeling software, used by the USDA Forest Service and others, models individual tree growth and requires users to apply a geographically explicit list of trees.

More specific information on the Levels and data needs for various activity estimations is included in the sections on specific activity estimations, as summarized in table 5-4. Reference table 5-5 for the structure of the accompanying Excel workbook. Below, the sections on individual methods describe the user input needed to use the Excel workbook.

Table 5-4. Overview of Managed Forest System Sections, Sources, and Methods

Section	Source/Forest Management Activity	Estimation Method
5.2.1	Silvicultural practices and improved forest management	Level 1: Applicable for basic projections of carbon flux reflecting broad forest maintenance practices or broad forest maintenance practices with a harvest, as well as scenario-based comparisons of reforestation, extended rotation, and avoided deforestation. The Excel workbook combines basic user-provided activity data with preprocessed lookup table values (carbon stocks and stock change specific to regions/forest type group/age classes/stand origin).
		Level 2: Applicable for basic projections, reforestation, extended rotation, and avoided deforestation. Level 1 quantification approach without the Excel workbook, using site-specific carbon stocks and carbon stock change data.
		Level 3: Applicable to a wide range of even-aged and uneven-aged silviculture and improved forest management practices. Inventory data combined with model simulations—e.g., FVS.

Section	Source/Forest Management Activity	Estimation Method
5.2.1	HWPs	Level 1: Excel workbook–facilitated computation to estimate the carbon stocks of products in use, products in SWDS, emissions from HWPs, and potential substitution benefits over a 100-year timeline. Results may or may not be combined with silviculture depending on user inputs (i.e., users may select the "Harvest" option which does not provide estimates of flux from tree growth).
		Levels 2 and 3: None offered.
5.2.3	Wildfire/ prescribed fire	Level 1: Excel workbook–facilitated computation. Applies preprocessed lookup table values offering estimated emissions according to three fire scenarios: severe, moderate, mild/prescribed burn. Estimates are grouped by forest type group and region. These results are generated independently from the silviculture calculations.
		Level 2: None offered.
		Level 3: Inventory data combined with model simulations—e.g., FVS with the Fire and Fuels Extension (FFE) or FOFEM (First Order Fire Effects Model).
5.2.4	Urban forest management	Levels 1, 2, 3: Selection of i-Tree tools based on the input data available and desired scope of emissions to account for.

Note that ongoing measurement and monitoring should take place after the forest management activity begins. This monitoring phase characterizes a project's impacts better than projections can. Annual measurements are usually either logistically impossible or too time consuming and expensive; rather, measurements are recommended every 5 years after the initial measurement. It is best practice to create and follow a measurement and monitoring plan in keeping with the goals of the project, and to keep organized records of measurements. This chapter does not include details on methods for ongoing measurement, which can be sourced from published literature and guidance such as Pearson et al. (2007).

Table 5-5. Structure of Accompanying Excel Workbook

Excel Workbook Component	Tab Identifying Color	Excel Tab	Description
Guidance and context	Yellow	Instruction and Context	Provides an overview of the purpose of the workbook and user instructions.
		U.S. Regions	U.S. regional delineations as applied in the guidance.
		Acronyms, Tabs, Citations	Lists abbreviations used in the Excel workbook, tabs and their contents, and citations. Also contains text that offers possible explanations where calculator outputs render estimated emissions.
User data entry	Red	User Data Entry	Here, users choose the management activity to quantify GHG flux for, then enter data and/or select from dropdown menus to define the quantification scenario(s) (e.g., baseline or management).
			Immediate detailed results for some management activities are also dynamically shown: ▪ Changes in ecosystem carbon stocks from activities included in section 5.2.1. ▪ Estimated GHG emissions from fire.

<table>
<tr><th>Excel Workbook Component</th><th>Tab Identifying Color</th><th>Excel Tab</th><th>Description</th></tr>
<tr><td rowspan="4">Main results</td><td rowspan="4">Dark orange</td><td rowspan="3">Forest Management & HWP Results</td><td>For clarity, summarized results are presented as separate categories:
▪ “Ecosystem Carbon Impacts from Forest Growth”: Change in living and dead carbon pools from the growth, mortality, and decay of forest biomass on site. “Ecosystem Carbon Impacts from Harvest”: Proportion of total ecosystem carbon stocks transferred to HWPs or emitted as a result of harvest.
▪ “Postharvest Carbon Impacts”: Harvested wood products in use, harvested wood products in SWDS, HWP emissions.
This results in an estimate of additional carbon sequestered as a result of forest management activity. If the activity includes a harvest, the summary tables reflect the complete accounting approach, reflecting the magnitude of ecosystem carbon left on site, as well as in wood products and ultimately emitted or stored in products or SWDS.</td></tr>
<tr><td>“Total AFOLU Biogenic Carbon Stock Change from Management Action”: A final result is also shown, which reflects the estimated stock change (flux) in AFOLU sector carbon. Negative values confer sequestration; positive values reflect either emissions (emissions at harvest, HWP emissions from decay) or decreased stocks/stock change (storage in harvested sawlogs etc.).</td></tr>
<tr><td>The “LCA Quantified Substitution Potential Associated with Harvest, Transport and Processing” area gives additional context, but is not presented as part of the total impact because some emissions fall outside the AFOLU sector.</td></tr>
<tr><td>Fire Results</td><td>Estimates of emissions for three fire activity scenarios. See section 5.2.3 for details.</td></tr>
<tr><td rowspan="4">Detailed results for reference</td><td rowspan="4">Light orange</td><td>Harvest Carbon Calculator</td><td>Offers detailed annualized estimates of emissions and storage of HWPs under different decay functions across the full 100-year accounting timeline (see section 5.2.2 for details). Examples of calculations are given in appendix 5-B.2.2.</td></tr>
<tr><td>Growing Stock Calculator</td><td>Offers detailed estimates of the harvest volumes by roundwood product types (see section 5.2.2 for details). Examples of calculations are given in appendix 5-B.2.2.</td></tr>
<tr><td>Potential Substitution</td><td>Quantified potential substitution benefits occur outside the AFOLU sector and are intentionally presented separately and not combined with the AFOLU totals, in accordance with IPCC reporting.</td></tr>
<tr><td>Various</td><td>Several other tabs with detailed outputs to calculations.</td></tr>
<tr><td>Lookup and reference values</td><td>Gray</td><td>Various</td><td>Back-end lookup tables are view-only. Additional gray-shaded tabs are included for transparency. Some include the values applied to calculations to render results.</td></tr>
</table>

5.2 Estimation Methods

5.2.1 Silvicultural Practices and Improved Forest Management

Method for Estimating Emissions or Carbon Removal from Silvicultural Practices and Improved Forest Management

- There are three Levels available for this sector, depending on data availability, user resources, and desired precision.
- For the Level 1 approach, the accompanying Excel workbook combines user inputs with relevant equations and regional lookup tables derived from the FIA Database (FIADB), and where appropriate, connects the silvicultural practices with the methods for quantifying harvest impacts, carbon stored in HWPs, and potential substitution.
- For a Level 2 approach, use the equations provided for the Level 1 approach accompanied with more site-specific removal or emission factors.
- The Level 3 approach requires users to combine inventory data with FVS modeling or a similar model to simulate management scenarios.

5.2.1.1 Description of Method

Forest management is commonly characterized in terms of silvicultural practices. These are practices that favor structural and compositional conditions that meet one or more landowner objectives. Traditionally, they have aimed to control the growth, composition, health, and quality of forests to meet objectives associated with commodity (e.g., timber) production with an eye to long-term sustainability. However, silvicultural practices are increasingly being used for other purposes such as to restore and enhance biodiversity; increase resilience against stressors such as insects, drought, or fire; and/or increase carbon accumulation and associated stocks.

Regardless of the management objective, silvicultural practices affect carbon dynamics, whether by increasing forest growth and changes in litter and detrital carbon stocks; altering the size distribution or composition of species or density of trees; or triggering a transfer of carbon from one pool to another.

If harvesting, some harvested carbon may ultimately be stored for years or centuries as a wood product, while some is left to decay and be released as emissions over shorter time scales. As such, the impact of silvicultural practices on carbon flux can manifest in a variety of ways such as a release of carbon to the atmosphere (i.e., emissions), storage of additional carbon in forests or resulting forest products, and/or additional climate benefits through substitution for more emissions-intensive materials (e.g., using wood as a building material instead of concrete).

When considering the appropriate Level for estimation approach, consider the availability of data and resources to perform sampling and modeling as well as the precision needed (e.g., a generalized estimate for basic understanding, a more precise one for reporting purposes). As shown in figure 5-3, the Level 1, Level 2, and Level 3 approaches in this section—and in the following sections—have different levels of accuracy and accessibility. See appendix 5-B.1 for a rationale of the method chosen to represent Level 1 in this section, including background on the lookup tables and underlying data sources. Appendix 5-C provides a list of some of the data gaps and future improvements.

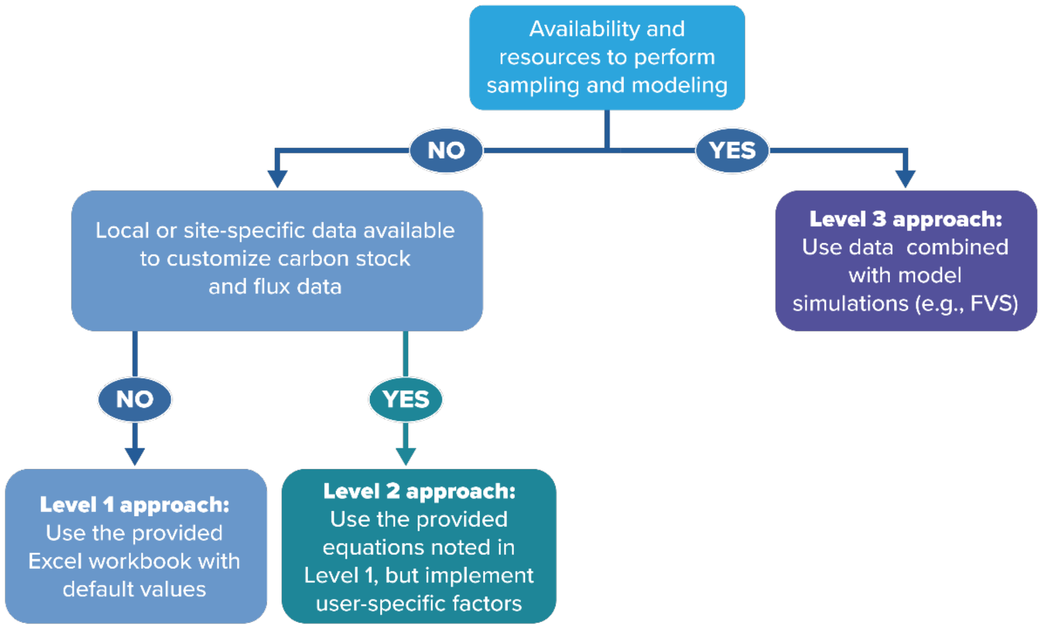


Figure 5-3. Decision Tree for Silviculture Practices and Improved Forest Management Levels

Level 1 Approach

The Level 1 approach is for entities with limited local data or knowledge of carbon quantification methods, or for entities seeking to produce a quick estimate of potential impacts from simple forest maintenance, reforestation, extending rotation, or avoiding deforestation. It relies on the accompanying Excel workbook, which has embedded lookup tables that offer regional default values for carbon stocks and stock change (i.e., “carbon removal factors” in this chapter). For some activities, the impact of harvest and the storage and substitution potential of HWPs can be quantified.

The lookup tables were constructed using data from the USDA Forest Service’s FIA program (Burrill et al., 2021). They offer average forest ecosystem carbon stocks and stock change values, organized by region, forest type group, stand origin, and stand age (see appendix 5-B.1 for methods). The carbon stocks and removal factors include all carbon pools except SOC and standing dead tree carbon for carbon removal factors. In the case of SOC, changes in soil carbon stocks are assumed to be *de minimis* over the timelines/temporal scales in question, and there is a lack of available data on the impact specific forest management practices have on SOC at the entity scale. In the case of standing dead tree carbon, FIA measures standing dead trees but does not track individuals after their transition to fallen dead wood; therefore, closed system accounting for change methods for that pool requires further research.

As stated in section 5.1.6, Level 1 offers users the ability to generate two types of estimates: basic projection and estimated impact of a management change. Table 5-6 describes data inputs to apply the Level 1 approach, as well as some caveats.

The basic projection estimation type offers a generalized projection of carbon stocks and stock change for the user-selected combination of region, forest type, age class, and stand origin. It is offered for forest maintenance with or without harvest. The section providing the estimated impact of a management change is applicable for a limited set of initial, generalized categories of silvicultural practices—extended rotation, reforestation, and avoided deforestation management options—and offers scenario-based comparisons (details on these practices are included in the section below and in appendix 5-B.2).

Given the granularity of the Level 1 approach, more sophisticated forest management interventions such as advanced silviculture or fertilizer applications are not included, but advanced users may be able to incorporate such operations in Level 3 approaches. Operations such as fertilizer applications can have gross GHG emissions associated with their production/application, as well as potentially a net reduction in GHG when considering resulting increases in forest growth/regrowth (as discussed in box 5-3). See appendixes 5-A.2 and 5-B.1 for more background information on these practices.

The more closely a user's selection of region, forest type group, age class, and stand origin align with the status of the current or proposed stand, the more likely results will be realistic. See the stratification discussion in section 5.1.5.1 for more on dividing management areas up into meaningful, internally homogeneous units (strata).

Where the specific forest type group, stand origin, or stand age class are not known, use the "unknown" option when entering parameters for the estimation of carbon stocks and flux in the Excel workbook. This option uses the area-weighted average value associated with the stand characteristic (or combination of characteristics, if multiple are unknown) within the selected region from the lookup table.

Box 5-5. Increasing the Transparency and Repeatability of Carbon Monitoring/Accounting Approaches through Open-Source Code

To increase the trust and accountability associated with carbon quantification tools, the data and associated computation processes used to develop emission/removal factors in this document is provided as an accompanying resource for these guidelines. Advanced users interested in evaluating how the lookup table values were derived and/or replicating or modifying the Structured Query Language (SQL) query approach used to construct the lookup tables can view the provided SQL code.

Table 5-6. Required Silviculture and Improved Forest Management User Data for the Accompanying Excel Workbook

Data Input	Description/How Data Are Sourced/Relevance
Area of intervention/ area of stratum	The area in which the entity anticipates undertaking the silvicultural activity. The Excel workbook assumes that entries are associated with a single stratum (such as a stand or group of stands). To generate results for multiple strata (such as forest stands with different stand origins), aggregate results from various strata with multiple runs of the tool. The workbook allows users to choose the units—acres or hectares. See section 5.2.1.2 for more information on how these area data values can be determined.
Region	The broad geographic region in which the silvicultural activity will take place. See figure 5-4 for a map of how the geographic regions are delineated.
Forest type group[a]	The forest type group that best matches the forest stand that will be subject to the forest management activity. See Burrill et al. (2021), appendix D, for detailed descriptions of the species composition of the forest types that constitute forest type groups. Choose "unknown" if the forest type group is not known.

Data Input	Description/How Data Are Sourced/Relevance
Stand origin	Whether the stand was planted or grew naturally. Choose “unknown” if the stand origin is not known.
Stand age class	The age range of the forest stand. Forests accumulate carbon at different rates, so knowing stand age class renders a more accurate estimate of annual and total carbon accrual from the anticipated activity. Choose “unknown” if the stand age class is not known. For planned reforestation activities, entries for this component are not considered.
Type of management treatment	The “User Data Entry” and “Forest Management & HWP Results” tabs display different options depending on the selection. ▪ **“Basic projection under forest maintenance (fm).”** Assumes no harvest**.** The results show the total amount of carbon sequestered up to 50 years from the present time (time 0). ▪ **“Basic projection under fm, with harvest.”** The results show the total amount of carbon sequestered between time 0 and the specified planned harvest time. Outputs are combined with the harvest carbon calculator outputs, including estimates of carbon flux in HWPs. ▪ **“Extended rotation.”** The results show the carbon benefit from deferring harvest in even-aged[b] stands. The results reflect the difference between projected carbon stocks under the “baseline” planned harvest date and the extended rotation harvest date. Outputs are combined with the harvest carbon calculator outputs, including estimates of carbon flux in HWPs for both the baseline and extended rotation scenarios. ▪ **“Avoided deforestation.”** The results show the carbon that remains stored as a result of avoiding deforestation that would have occurred at time 0 under the baseline scenario, including the estimated carbon sequestration over 50 years (i.e., includes the benefit of sequestration that would have been foregone if the deforestation event happened). ▪ **“Reforestation (natural)”** or **“Reforestation (planted).”** The results show the projected total amount of carbon sequestered over 50 years. The baseline scenario is assumed to be no carbon accrual. ▪ **“Harvest.”** This option does not compare silvicultural treatments and just quantifies GHG flux from harvest at time 0**.**
Length of rotation/harvest	If “Basic projection under fm, with harvest” or “Extended rotation” options are selected, users must enter the rotation date (5-year increments). For extended rotation, 2 rotation years are needed: (1) harvest under the baseline scenario and (2) harvest under the extended rotation scenario.

[a] The forest types in this chapter correspond to the “forest type groups” described in the FIADB phase 2 user guide (Burrill et al., 2021, appendix D). These forest types are also listed explicitly in table 5B-11.

[b] Even-aged forests typically consist of trees that are in a limited number of age classes (one or two, e.g., 0 to 20 and 21 to 40 years old).

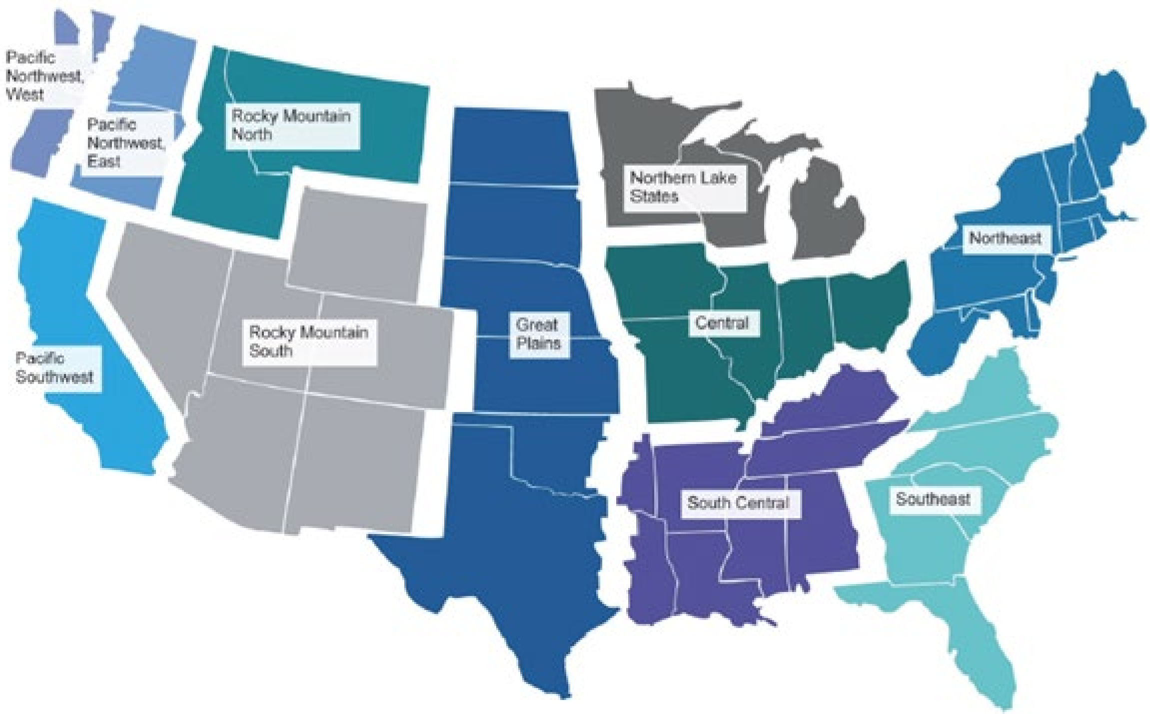


Figure 5-4. Forest Regions Applied to Organize Lookup Table Values for the Silviculture, Fire, and HWP Components of This Chapter

The methods and equations for combining lookup table values with activity data are described below. For some scenarios a user might create, seemingly illogical values (such as net emissions from a forest stand rather than growth) can occur if the lookup table data are generated from sparse forest inventory data. While these values could be valid—for example, in areas where fire, insects, or disease are causing net emissions from forests—care must be taken when interpreting them. If a value deemed illogical is rendered, options include:

- Choose "unknown" for the age class or stand origin in the Excel workbook. This will increase the number of values used to produce the lookup table estimates and may yield more reliable results.
- Undertake a Level 2 approach, looking elsewhere for more site-specific average carbon stock or stock change estimates to integrate as variables into Level 1 formulae described below.

See appendix 5-A.2.6 for more background information on the lookup tables used for this approach.

Any attempt to project forest growth dynamics should consider results within the context of location-specific disturbance risks (e.g., fire, insect, disease, temperature extremes, flood, and drought) and planned management and oversight to maintain the forest stand and its carbon stocks. The default lookup table values for carbon stocks and carbon stock change (i.e., carbon removal factors) have been produced using FIA data, so they inherently reflect background rates of tree growth and mortality seen across current U.S. landscapes. Where higher mortality is expected or observed during measurement and monitoring phases, users may need to consider discounting projections of carbon accumulation or taking a Level 2 approach that applies more site-specific removal factors.

Although the Excel workbook offers projected carbon sequestration for included activities for up to 50 years into the future, the further into the future a projection is made, the greater the uncertainty. In the Excel workbook, cells for years 25–50 in the "Detailed Ecosystem Carbon Scenario Projection" part of the "User Data Entry" tab are shaded as a reminder to users to consider the high uncertainty associated with projections that far into the future.

Ecosystem Carbon Accounting with HWP Carbon Accounting Linkage

This chapter presents silvicultural practices and improved forest management (this section) and HWP (section 5.2.2) separately, though these activities are connected through harvesting. The "ecosystem" side of carbon accounting described in this chapter covers carbon accumulation in living and dead biomass, as well as living and dead biogenic carbon flux because of harvest, such as that occurring from decomposition of logging residues. The HWP section considers the harvested wood that reaches the mill and is converted to wood products and mill residues (products in use), some of which decompose or ultimately end up in SWDS.

This guidance and the accompanying Excel workbook, under a Level 1 approach, connect the ecosystem accounting with HWPs by presenting HWP results in the context of FIA-based estimates of total ecosystem carbon stocks and management scenario impacts prior to harvest (equation 5-1 and equation 5-2) and estimates of logging residues calculated using regional factors derived from the literature (i.e., Smith et al., 2006; Johnson, 2001).

When the user selects activities that result in a harvest (i.e., "Basic projection under fm, with harvest," or "Harvest,"), the Excel workbook offers two options, advanced and default, based on user-supplied yes/no answers to the question "Do you know what your harvest volume is?" For extended rotation scenarios, only the default data option is available.

- **Advanced option:** Enter harvest data such as known harvest volumes or weights from logging/mill receipts or consultant reports, wood types (hardwood, softwood, unknown) and product types (sawlogs, pulpwood, fuelwood, unknown) as totals or per-acre values, as well as percentage of total growing stock harvested.
- **Default data option:** Uses default FIA data on regional growing stock volumes (cubic foot net volume per acre based on user-selected parameters around region/forest type group/ stand age class/stand origin) for medium- and large-diameter stands to estimate harvest amounts. These growing stock volume default values delineate what part of the total live tree biomass carbon pool could be targeted for harvest. However, these estimates do not definitively reflect the total volume of wood potentially removed at harvest, given that nonmerchantable trees (not part of growing stock volume estimates) are often cut and taken to the mill to produce pulpwood or used for fuelwood. Therefore, these values are used as a starting point to quantify the wood taken to the mill but adjusted using published ratios from Johnson et al. (2001) to incorporate region-specific estimates of fuelwood or pulpwood biomass that the cubic foot net volume estimates do not capture. For the basic projection and "Harvest" options, the growing stock volumes can be discounted by the entered harvest area percentage. For the "Extended rotation" management option, 100 percent of the area is assumed to be harvested as extended rotation forest management is assumed to be an even-aged forest management practice.

With these data, estimates of the carbon flux associated with HWPs and the GHG flux from potential substitution can be calculated (see section 5.2.2 for more on the HWP components of the Excel workbook).

The Excel workbook presents the results in two ways, depending on the management scenario selected:

- Net carbon impacts of the planned management activity
- Carbon stock changes from time 0 to the time of harvest or year 50

The following sections describe the calculations for the various management scenarios.

Basic Projections

To project the carbon impact of maintaining a forest stand as forest cover, the Excel workbook runs equation 5-1 for 5-year intervals between time 0 and year 50 or the date of harvest, then uses equation 5-2 to calculate the total amount of carbon sequestered over the scenario time period (see box 5-6 for a definition caveat). If a harvest is planned, the projection ends at the harvest year entered by the user.

Box 5-6. “Removals”

In this chapter, “removals” is used interchangeably with “sequestration” and thus refers to a removal of carbon from the atmosphere in keeping with carbon accounting terminology precedence.

In the FIADB (Burrill et al. 2021), and in the context of forest management operations, “removal” is used to describe harvest operations when trees are removed from a site.

Equation 5-1: Five-Year-Interval Gross Carbon Removals

$$Five\ Year\ Interval\ Carbon\ Removals_{rtpai} = A \times F_A \times RF_{rtpai} \times F_m \times CO_2MW \times 5i$$

Where:

Five Year Interval Carbon Removals$_{rtpai}$	=	5-year time step CO_2 removals due to forest growth in region *r,* forest type group *t,* with stand origin *p*, age class *a,* and 5-year interval *i* (metric tons CO_2)
A	=	area of stratum (ha or ac)
F_A	=	area unit conversion factor; 2.407 if hectares are entered, 1 otherwise
RF_{rtpai}	=	removal factor (i.e., carbon stock change) for region *r*, forest type group *t*, stand origin *p*, and age class *a*, with *a* adjusted for time interval *i* (U.S. tons C/acre/year); time interval adjustment occurs because the age class of a stand changes through time, so different removal factors must be used as time progresses (see equation 5-B-2)
F_m	=	U.S. to metric ton conversion factor (0.907 metric tons/U.S. ton)
CO_2MW	=	ratio of molecular weight of CO_2 to carbon = 44/12

In the Excel workbook lookup tables, if a given combination of the classification variables chosen by the user does not exist, the removal factor data are aggregated hierarchically, starting with stand origin, then stand age, then forest type group, until a valid combination is found.

Equation 5-2: Total Gross Carbon Removals

$$Total\ Carbon\ Removals_{rtpah} = \sum_{i}^{h} Five\ Year\ Interval\ Carbon\ Removals_{rtpai}$$

Where:

$Total\ Carbon\ Removals_{rtpah}$	=	the sum of *Five Year Interval Carbon Removals*$_{rtpai}$ (metric tons CO_2) for the combination of the above-defined stand characteristics *r*, *t*, *p,* and *a* at scenario time *h*
i	=	5-year increment
h	=	the final cumulative increment endpoint (e.g., the end of the last period of carbon accumulation)

In the case of basic projection over 50 years, *h* =10 (because increments are in 5 years, 5*h* = 50 years). In the case of basic projection with harvest, *i* = 5 and *h* = the year the user chose as the harvest year divided by 5 (because increments are accounted for in 5-year intervals)

For the “Basic projection under fm, with harvest,” “Extended rotation,” and “Harvest” scenarios, the Excel workbook uses equation 5-3 to estimate carbon in logging residues, which reflects the CO_2 emissions associated with the decomposition of biomass left on site (i.e., stumps, branches, leaves) conservatively assuming release of these emissions immediately after harvest. The logging residue fractions used in equation 5-3 are generated from a lookup table derived from Johnson’s (2001) tables[4] and are selected based on the chosen region and wood type. If wood type is unknown, harvested growing stock volume is distributed across wood and/or product types as described in section 5.2.2. Residue fractions of harvest are calculated as logging residues from all sources divided by the total harvest from all sources (growing stock and nongrowing stock). For example, for the North Central region and softwood trees harvested, the logging residue fraction is calculated as 97,775 ÷ 381,515, or 0.26 (i.e., 26 percent of the overall harvest was left behind as residues).

Equation 5-3: Logging Residue Emissions at Harvest

$$EH = RW_M \times F_{LRrw}$$

Where:

EH	=	logging residue emissions at harvest (metric tons CO_2)
RW_M	=	roundwood at mill after growing stock calculator adjustments and unit conversions to metric tons CO_2, as described in section 5.2.2
F_{LRrw}	=	logging residue factor associated with region *r* and wood type *w*, calculated from Johnson (2001) tables, as described above

Estimated Impact from Management Change: Extended Rotation

For extended rotation scenarios, the Excel workbook runs equation 5-1 and equation 5-2 for both the baseline and intervention scenarios. In the case of extended rotation, the variable h is set to h_b for the year of the baseline harvest and h_e for the year of the extended rotation harvest. In the Excel

[4] Specifically, the values are derived from regional tables—table 2.9 (Northeast), table 3.9 (North Central), table 4.9 (Southern), table 5.9 (Rocky Mountain), and table 6.9 (Pacific Coast)—within Johnson (2001).

workbook, the growth of the forest stand under the two scenarios (baseline and extended rotation) is shown in 5-year increments, both as the stocks and as flux (5-year change), in the "User Data Entry" tab in the "Detailed Ecosystem Carbon Scenario Projection" part of the display. Extended rotation activities are assumed to be undertaken in even-aged stands, and therefore 100 percent of the stratum/project area is assumed to be subject to harvest. Background on extended rotation is available in appendix 5-A.2.2.

To ensure accounting conservatively captures postharvest regrowth under the baseline scenario, after the baseline harvest date, the age class (a) for the baseline case is reset to the 0–20 age class, and the appropriate removal factors from the FIA lookup table for the 0–20 age class, combined with the same region/forest type group/stand origin selections, are used in equation 5-1 and equation 5-2 to grow the harvested stand until the date at which the user chose to harvest under extended rotation, at which point overall impacts of extending harvest can be calculated using equation 5-4, which describes the net impact of extending the rotation length (i.e., carbon removals from the atmosphere).

The results from equation 5-2 under the baseline and extended rotation scenarios are then brought over to the "Forest Mgmt & HWP Results" tab in the Excel workbook to complete the scenario projection inclusive of the postharvest ecosystem carbon impacts and HWP and LCA analyses[5] (section 5.2.2). The ultimate benefit is the difference between the final estimates—"TOTAL AFOLU (Forest) Biogenic Carbon Stock Change (Flux) from Management Action and Harvest"—for the two scenarios, which embodies the total impact of extending the rotation length in terms of both ecosystem impacts and postharvest carbon storage and emissions.

Equation 5-4: Net Impacts

$$\begin{aligned} Net\ Impacts &= Total\ Carbon\ Removals_{management\ intervention\ scenario} \\ &\quad - Total\ Carbon\ Removals_{baseline\ scenario} \end{aligned}$$

Where:

Net Impacts	=	estimated impact change (metric tons CO_2)
Total Carbon Removals	=	total carbon removals (metric tons CO_2)

Estimated Impact from Management Change: Reforestation

For reforestation activities, the Excel workbook runs equation 5-1 and equation 5-2 for the intervention scenario to reflect carbon sequestration of either a planted or a natural stand of a given forest type and the appropriate age class, based on the years of growth since time 0. Under the baseline scenario, it is assumed no significant accrual of carbon stocks would happen in the absence of natural or reforested stands. In other words, the stand is assumed to start with the user-selected parameters for region, forest type group, and stand origin, and begin growing with the 0–20-year age class; as time passes, the age class transitions to the next higher one, as described above, so updated removal factors are used through time.

The Excel workbook runs equation 5-4 (using zero for $Total\ Carbon\ Removals_{baseline\ scenario}$) to calculate the net impact of the activity. This is because the Level 1 approach assumes the baseline scenario has zero net carbon flux (i.e., without the reforestation effort, the area would have zero

[5] This is the only full side-by-side analysis of harvest scenarios enabled by the accompanying Excel workbook because "Extended rotation" is the only available scenario comparison (i.e., estimated impact from change in forest management activity) that involves harvest in both scenarios.

change in carbon stocks). Where baseline carbon stocks are expected to accrue (i.e., trees would likely grow and accumulate more than a *de minimis* amount of carbon in the absence of a reforestation activity), it may be more appropriate to use a Level 2 approach that models baseline carbon accumulation and compares it to the reforestation scenario using equation 5-4. Background on reforestation is available in appendix 5-A.2.3 and 5-B.1.2.

Estimated Impact from Management Change: Avoided Deforestation

For avoided deforestation activities, the Excel workbook runs equation 5-1 and equation 5-2, as with the "Basic projection under forest maintenance" (no harvest) scenario. However, it also presents results from equation 5-5, and equation 5-6, allowing the user to add the standing stocks at year 0 (the assumed date of deforestation under the baseline scenario) of the forest to the calculations of annual removals. Under the baseline scenario, the forest is cleared immediately following time 0 and future carbon the forest could have sequestered is foregone. In the avoided deforestation scenario, the immediate loss of biomass carbon stocks is prevented, and carbon may be allowed to continue to accumulate over time in the vegetation. Background on avoided deforestation is available in appendix 5-A.2.4.

The calculation steps are:

1. Calculate forest carbon accumulation as described above using equation 5-1 and equation 5-2; results are associated with the avoided deforestation treatment. For the baseline scenario, deforestation is assumed to occur immediately after the starting point (year 0); the foregone sequestration takes place over subsequent years up to year 50. Therefore, *h* in
2. Equation 5-2 should be 10 (because increments are in 5 years, 5*h* = 50).
3. Calculate total standing stocks (equation 5-5).
4. Calculate benefits by adding total standing stocks to total carbon removals (equation 5-6).

In other words, apply equation 5-5 and equation 5-6 for total standing stocks and total carbon removals; for the baseline scenario apply only equation 5-5 for time 0, as harvest is assumed immediately following time 0.

Equation 5-5: Total Standing Stocks

$$Total\ Stock_{rtpa} = A \times F_A \times CS_{rtpa} \times F_m \times CO_2MW$$

Where:

$Total\ Stock_{rtpa}$	= total stocks of CO_2 for region r, forest type group t, with stand origin p, at age class a (metric tons CO_2)
A	= area of stratum (ha or acre)
F_A	= area unit conversion factor; 2.407 if hectares are entered, 1 otherwise
CS_{rtpa}	= carbon stocks (U.S. tons/acre) for region r, forest type group t, with stand origin p, at age class a (U.S. tons C/acre); these values are from estimates found in FIA-derived lookup tables and include aboveground and belowground live and dead carbon, SOC, DDW carbon, and litter carbon (see equation 5B-1)
F_m	= U.S. to metric ton conversion factor (0.907 metric tons/U.S. ton)
CO_2MW	= ratio of molecular weight of CO_2 to C = 44/12

Equation 5-6: GHG Impacts from Avoided Deforestation

$$AvoidedDef_{rtpa} = Total\ Stock_{rtpa} + Total\ Carbon\ Removals_{rtpa}$$

Where:

$AvoidedDef_{rtpa}$	=	benefits from avoided deforestation activities (metric tons CO_2)
$Total\ Stock_{rtpa}$	=	total stocks of CO_2 in region *r,* forest type group *t,* with stand origin *p,* at age class *a* (metric tons); see equation 5-5
$Total\ Carbon\ Removals_{rtpa}$	=	total carbon removals (metric tons CO_2); see equation 5-2 (this is part of the equation because most U.S. forest stands are accumulating carbon; total carbon removals might be small or nonexistent for old growth forests)

The maximum value of 10*h* used under the Level 1 approach is 50 years, but projections this far into the future should be considered in the context of management plans and capacity (e.g., efforts to maximize survival and growth) as well as the potential for natural disturbances.

Level 2 Approach

The Level 2 approach is identical to the Level 1 approach except that rather than using Level 1's default data it uses locally representative data to create site-specific emission factors. Choose this approach where:

- Locally representative data are available from an existing forest inventory.
- Assumptions or context applied in the development of the default data do not fit the silvicultural activity of interest (i.e., do not reflect the unique attributes and delineation of forest stands within an entity). In this case, use alternative sources of carbon data to develop emission or removal factors, such as those from published literature, or USDA Forest Service FIA estimates such as found in the EVALIDator[6] or DATIM tool. Several potential sources of data and other tools for carbon estimation are presented in appendix 5-A.6. The updated *Estimates of Forest Ecosystem Carbon for Common Reforestation Scenarios in the United States* (Hoover et al., 2023) may be of particular use as an alternate dataset: It offers FVS-generated forest ecosystem carbon yield tables for a set of common reforestation scenarios, representing stand-level total volume and carbon stocks as a function of stand age, for 13 forest types within the United States.

When using a Level 2 approach, refer to the Level 1 approach and replace lookup table variables (removal factors and standing stocks) with alternate available data.

Level 3 Approach

Level 3 requires more resources and time, as well as the ability to conduct detailed and statistically appropriate forest carbon inventories coupled with appropriate biometric models (e.g., live tree allometry) and projection systems (e.g., FVS).

[6] EVALIDator draws from FIA data to produce estimates and sampling errors for selected forest attributes for an area of interest. It allows users to designate their own polygons. See https://www.fs.usda.gov/ccrc/tool/forest-inventory-data-online-fido-and-evalidator for more information.

Establishing Forest Carbon Inventories

Forest carbon inventories are composed of observations and measurements from a series of plots in the forest, describing the trees in each plot—species, diameter, height, etc. From these measurements, stand-level estimates of tree density (trees per unit area), basal area (cross-sectional bole area at 1.4 meters [4.5 feet] above the ground), species composition, and tree volume and biomass can be computed.

The description below is a very general discussion of some principles of forest carbon inventory establishment. It is not comprehensive guidance, as inventory methods for estimating the carbon among forest ecosystem carbon pools are well developed and fairly standard. Methods for measuring forest ecosystem carbon stocks are described in a variety of publications, including the IPCC *Good Practice Guidance for Land Use, Land Use Change, and Forestry* (IPCC, 2003), Pearson et al. (2007), and Hoover (2008), among others. As the FIA program is the federal program tasked with providing national-scale estimates of the U.S. forest carbon stocks/flux, documented inventory procedures from this program (USDA Forest Service, 2010a, 2010b) are also available and can serve as a basis for many facets of entity-level carbon reporting.

Detailed methods for forest carbon inventory are well described and available from a variety of sources, such as those listed in box 5-7.

Box 5-7. Resources for Establishing Forest Inventories for Carbon Estimation

- *Measurement Guidelines for the Sequestration of Forest Carbon* (Pearson et al., 2007): https://www.nrs.fs.usda.gov/pubs/gtr/gtr_nrs18.pdf
- *Standard Operating Procedures for Terrestrial Carbon Measurement* (Walker et al., 2018): https://winrock.org/document/standard-operating-procedures-for-terrestrial-carbon-measurement-manual/
- *Sourcebook for Land Use, Land-Use Change and Forestry Projects* (Pearson et al., 2005): https://openknowledge.worldbank.org/bitstream/handle/10986/16491/795480WP0Sourc0CF0Projects00PUBLIC0.pdf
- Winrock's sample plot calculator spreadsheet tool (Walker et al., 2014): https://winrock.org/document/winrock-sample-plot-calculator-spreadsheet-tool/
- *Allometric Equation Evaluation Guidance Document* (Walker et al., 2016): https://winrock.org/wp-content/uploads/2018/08/Winrock-AllometricEquationGuidance-2016.pdf
- *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Hoover et al., 2014). https://www.usda.gov/sites/default/files/documents/USDATB1939_07072014.pdf
- *Module C-CS: Calculations for Estimating Carbon Stocks* (Goslee et al., 2016). https://winrock.org/wp-content/uploads/2018/08/Winrock-Guidance-on-calculating-carbon-stocks.pdf

For small entities such as farm woodlots or tree and forest stands, a complete inventory of carbon across relevant pools, strata, and project land may be feasible. For large areas, such an inventory is likely both infeasible (in terms of time and resources) and unnecessary, as a well-designed sampling strategy can render results with low uncertainty. Sampling involves installing sample plots in the project area using a sample design, which could include stratification into subregions (see section 5.1.5.1 for more information on stratification). Forest inventories commonly use a number of plot designs; a full discussion is beyond the scope of this document. The number of plots used affects the reliability of resulting estimates; using more plots generally leads to more trustworthy results. To improve results and lower costs, stratifying the area into homogeneous subregions is often a good practice. Certified professional forestry consultants can also provide support in forest inventory.

For carbon accounting, the most important data collected on inventory plots are related to the tree's geometry, such as its dbh and height. To translate these measurements into carbon estimates, allometric equations—which describe the relationship between these measurements and a tree's volume or biomass—are used. These equations are either species-specific or refer to a group of species with similar geometric and wood properties. Several comprehensive, nationally consistent, and widely cited sets of allometric equations for all tree species in the continental United States are available (e.g., Westfall et al., 2023; Jenkins et al., 2003; Chojnacky et al., 2014; Woodall et al., 2011): these may be a good place to start for entities wishing to produce carbon estimates based on their own forest inventory data. The Forest Service FIA program released updated national scale volume and biomass (NSVB) estimators (Westfall et al., 2023) which are based on whole stem volume equations that are additive across the components: stump, merchantable bole, and nonmerchantable top. This more accurately reflects regional and species-specific patterns of biomass distribution and growth.[7]

To arrive at sample-based estimates, tree-level biomass or carbon estimates are aggregated to the plot level, and these plot values are expanded to population-level estimates of total carbon stock, average carbon stock, and carbon flux using standard statistical estimators (Smith et al., 2003). There exist various generic values for stocks and carbon densities in the literature (e.g., U.S. DOE, 1992; Smith et al., 2006; IPCC, 2003, 2006), and more site-specific, detailed values can be derived using FIA's reporting tools such as the FIADB or by undertaking a carbon inventory (described in section 5.2.1 under the Level 3 approach). As this is an emerging field of research and data compilation (see Martin et al., 2018), site-specific values should be considered superior to generic values, especially for the more complex dead wood components (Harmon et al., 2013) that should incorporate decay reduction factors (Domke et al., 2011).

Using FVS for Carbon Modeling

The USDA Forest Service's FVS software (USDA Forest Service, 2022c) is an individual tree-level model that can simulate a variety of forest management practices. It enables forest growth simulation, quantifying vegetation change in response to natural succession, disturbances, and management. It applies inventory data to model forest growth and yield, estimating carbon as a function of those estimates. As such, it needs data such as slope, elevation, site productivity (i.e., site index), inventory design specifications, species, tree diameters, etc. Default values are available for some variables, but model outputs rely heavily on the assumption that standard forest inventory data are used. Those employing FVS to model stand carbon dynamics into the future should be aware that the model does not account for projected climate impacts on growth (if one does not request the FVS climate extensions) and that future carbon estimates (i.e., 20+ years out) have high uncertainty. Note that FVS was developed as a tool for foresters, and therefore may be difficult for untrained users. FVS training is available from USDA (https://www.fs.usda.gov/fvs/training/index.shtml).

[7] For more information, visit: https://www.fs.usda.gov/research/programs/fia/nsvb

See Hoover and Rebain (2011) for more information on employing FVS for carbon estimation and the FVS carbon reports website for more information and resources on FVS (USDA Forest Service, 2022c).

5.2.1.2 Activity Data

For silvicultural practices, activity data typically define the area of intervention, the rate or degree of intervention (e.g., acres per year), land-use change, land cover change, or management activities. For small landowners, it may be possible to delineate an area of land cover change using simple distance measurements or with the aid of GPS. Surveyors' reports, maps, aerial imagery, online State/community/town geographic information systems (GIS), or online tools such as Google Earth (see appendix 5-A.1.1) may also provide this information.

For more complex land holdings where different interventions are planned across noncontiguous land areas (several forest patches), or where land area is made up of a heterogenous set of characteristics such as soil type, vegetation cover, and disturbance history, it may be necessary to stratify the land into homogenous stands (see stratification discussion in section 5.1.5.1). Remote sensing or aerial photography (as simple as using Google maps or local/State GIS web portals) can be useful for any landowner, but they are especially useful for larger land units. Even where a single type of silvicultural activity is being considered, there might be a need to stratify based on conditions and species compositions. For example, a landowner may want to extend the rotation time for two different stand types on their property: a Douglas fir/ponderosa pine stand and a lodgepole pine stand. Having species-specific activity data allows for the application of species-specific emission or removal factors, rendering potentially more accurate quantification outputs.

Equally important, but beyond the basic management interventions outlined in section 5.2.1.1, a forest holding may also have a variety of complex interventions comingled across space and time for which a Level 3 approach may require advanced FVS customization of management specifications in order to estimate GHG results (Hoover and Rebain, 2011). In many cases, landowners will have estimates of land area and management objective readily available for use as activity data. For example, they may already have an estimate of the area of land they wish to reforest, which they defined using a standard GPS device. In other cases, due to the size of the property or the heterogenous nature of the land cover, measurement using a GPS device or Google Earth may be less practical. In those cases, there are online tools that may offer a cost-effective way to stratify land and quantify the area in which a silvicultural intervention can take place (i-Tree, 2022a). See appendix 5-A for a description of how to use i-Tree Canopy or Google Earth for estimating the area of each stratum.

Tools and online software platforms are continuously emerging to support entity-scale decision making around climate-smart forestry and policies. These combine GIS mapping and interactive maps to produce custom estimates of forest carbon flux. One such tool is the Measurement Reporting and Verification (MRV) Toolkit (https://www.goeslab.us/forest-carbon-mrv-tool.html), developed by Michigan State University. It is designed to support users in developing site-specific emission or removal factors from forest inventories and combine them with activity data to render estimates of GHG flux from forest management practices. It offers a library of tree volume/biomass equations and activity data from remote sensing or land-use change data. Using these data, the MRV Toolkit estimates emissions and carbon removals for a selection of land use and silviculture situations or scenarios, either as a single practice or as a sequence of linked practices. It supports a complete statistical allocation of a field-based sample plot frame for a forest inventory, or a more simplified use of default values that circumvents the need for a more resource-intensive forest inventory. Appendix 5-A.6 provides carbon estimation tools and data sources.

5.2.1.3 Limitations and Uncertainty

Limitations

The Level 1 approach offered in this section does not fully cover the breadth of silvicultural practices entity owners might seek to adopt. The diversity of traditional silvicultural practices and emerging techniques for enhancing forest resilience and ecosystem service provision, combined with the innumerable combinations of vegetation, climate, and site conditions found across the United States, presents significant challenges in providing consistent and broadly accessible ways to credibly estimate GHG flux.

The selection of variables used to group FIA plots for the Level 1 analysis does not fully account for the impact of management practices within silviculture. While FIA offers a rich source of data on forest stand attributes, and remeasurement of plots allows for the quantification of carbon stock change, the impacts of specific management practices are harder to assess. A more robust modeling approach is needed for these purposes but is beyond the scope of this version of the report.

Additionally, site conditions at time 0 for many forest management operations can be important for subsequent forest regrowth and carbon accumulation, but they vary widely, and the Excel workbook currently does not allow the addition of site classification variables. Further research is needed to build a more robust modeling platform and approach for understanding the impact of a broader set of management interventions on contemporary forest carbon dynamics.

Future iterations of this guidance will continue to bring in the best science and attempt to present it in a manner that enables climate-smart decision making for a broad range of users. Emerging online tools, forest modeling advancements, and advances in carbon accounting approaches will continue to provide solutions to today's accounting barriers.

The calculations proposed for this section and section 5.2.2, along with associated data inputs, characterize a large portion of the journey carbon takes from the forest ecosystem back to the atmosphere; however, they are incomplete. The methods provide an approach for estimating carbon that is sequestered in a forest through growth, with additional carbon being potentially sequestered by a limited set of forest management interventions. They also provide an estimate of potential emissions from logging residues left on site after harvesting, but these estimates are based on a broad national default wood utilization rate. Section 5.2.2 accounts for the rest of the carbon's journey though wood products in use and in SWDS. Always consider the full journey of carbon through both the ecosystem side and the HWP side for complete accounting.

There remain notable gaps in the accounting due to a lack of existing data and research to draw from. These include, but are not limited to:

- Connections between known harvest volumes/wood mass (across a range of tree sizes, species, and quality) and the HWP calculations. This includes the application of default values from Smith et al. (2006) and Johnson (2001) that may not reflect contemporary forest management, harvesting, and mill practices.
- Emissions-at-harvest estimates, which need further refinement to reflect the diversity of wood utilization outcomes of harvest.
- Modeling various forest management practices and postharvest growth across the different forest ecosystems. This persistent research need can be met using biometric models such as FVS as part of Level 3 approaches.

- Better understanding of the impacts forest management and harvest equipment have on soil carbon stocks.
- Better estimation/modeling of the lateral transfer of carbon between live tree and standing/down dead tree pools. As the official U.S. forest inventory is used to estimate carbon dynamics associated with the Level 1 approach in this guidance, refined alignment between fixed-area sample plots for standing trees and line-intersect sampling for down dead trees is needed.
- Refined estimates of forest carbon pools beyond aboveground live trees such as DDW, understory vegetation, belowground carbon roots associated with live/standing trees and stumps, and soils/litter. In particular, while soil is the largest stock of carbon in forest ecosystems, current FIA sampling density and frequency limit the ability to characterize soil carbon change. As such, soil carbon was a carbon pool omitted from the default tables.
- Climate change impacts on tree growth and disturbance likelihood (e.g., wildland fire, insects and disease).

These are active areas of research, the results of which may be important to incorporate in future versions of these guidelines. See appendix 5-C for a more complete exploration of research gaps.

Uncertainty

There are many sources of uncertainty associated with estimating the carbon impacts of silvicultural systems, such as the compounding of errors associated with the estimates of carbon stocks across a diversity of pools, stand structures, species compositions, and site qualities subsequent to management actions. Perhaps the largest source of uncertainty is the application of carbon stock and growth factor lookup tables partitioned with a relatively small number of classification variables to a specific stand.

The development of methods for estimating uncertainty of estimates applied to small areas is an active area of research. If plots are collected within the stand being assessed, standard uncertainty estimation techniques apply. However, if there are no plots in the area of interest, model-based approaches are commonly used, and generating uncertainty estimates from model outputs is challenging.

In addition, the estimation of non-CO_2 GHG fluxes is very uncertain and must be used with some degree of caution. This is especially true for N_2O in all activities and CH_4 in forest establishment. Considerably more research is needed in this area.

Another uncertainty in most estimates is the fraction of standing dead biomass. Based on previous work (Woodall and Monleon, 2008), it is believed to be small, but the variation with forest types, stand age, conditions, and activities is large. With default values, this may be a challenge to the final estimation. If direct measurements are to be made on site, the standing dead can be measured along with standing live biomass. This approach may have special benefit if the site being cleared has been intensely damaged by pests or disease.

The computation of whole tree biomass from allometry is another challenging source of uncertainty. There is literature on allometry for North American tree stem volumes and biomass, but less on whole tree volume and biomass. The updated NSVB estimators (Westfall et al., 2023), adopted by the FIA program in September 2023, are integrated into the lookup table values in the accompanying Excel workbook. These data are based on actual tree measurements and offer many advantages in terms of lowering uncertainty and better reflecting whole tree biomass as compared to the former component ratio method (Woodall et al., 2011). However, no estimate of uncertainty is offered in this guidance under the Level 1 approach.

This may be important because most landowners will not have the ability or interest to conduct their own destructive tree sampling to extract local whole tree biomass allometry (i.e., an IPCC Tier 3 approach). Beyond aboveground live tree carbon estimates, there can be even greater uncertainty associated with the additional ecosystem components of standing dead trees, soils/litter, belowground pools associated with live and dead trees, and DDW. Proper accounting for changes in these forest carbon pools is needed to reduce uncertainties associated with forest carbon dynamics, especially in the context of natural disturbances and management actions (sometimes comingled across space and time).

In conclusion, the Excel workbook and the treatment of silvicultural activities in this guidance do not give a full accounting of carbon dynamics resulting from forest management. A number of simplifying assumptions were made, such as carbon neutrality pretreatment (in the case of reforestation) or post-treatment (in the case of extended rotation and harvest). Furthermore, certain carbon components found in the FIA-derived lookup tables, such as transition of standing dead trees to the DDW pool, are not measured directly but inferred through model outputs. These assumptions and gaps in the accounting balance sheet add to uncertainty but are actively being addressed with new research and modelling approaches.

5.2.2 Harvested Wood Products

Method for Estimating Carbon Storage and Emissions and LCA-Quantified Substitution Impacts From HWPs

Production Approach (for Stocks of Carbon Stored in HWPs)

- For Level 1, the Excel workbook computes results using basic user inputs. It applies the IPCC-guided production approach of HWP carbon accounting, in which carbon contained in wood and wood products remains in the account of the producing entity regardless of where the wood or wood product is used (Brown et al., 1998).
- This approach is broadly applicable, but the numeric tables and other values are unique to U.S. applications for estimating the annual changes in carbon stocks in products in use and in SWDS as well as the annual carbon emissions to the atmosphere.
- Use the Excel workbook to estimate the amount of HWP carbon from the current year's harvest that will be stored in the HWP pool over the next 100 years.
- Two decay functions are available to model products in use lifespans before disposal: the more traditional "exponential" function and a novel alternate "chi-square, gamma" function. The latter is the default function applied in the Excel workbook but users can also obtain results from using the traditional "exponential" function.

LCA Approach (for HWP GHG Emission and Substitution Impacts)

- For Level 1, the Excel workbook computes results using basic user inputs. It applies the LCA method to quantify GHG emissions for HWPs as kg CO_2-eq emitted per kg of an HWP on an oven-dry basis. The LCA approach is guided by the ISO 14040 and 14044 standards.
- The quantification of GHG emissions in this guidance refers to cradle-to-gate LCA, which includes life stages of HWPs from forest harvesting to product manufacturing.
- The HWP substitution factor lookup tables are based on the GHG emissions avoided when substituting wood for nonwood products in a functional equivalent application.

- The substitution factors are provided to help forest landowners quantify and compare the carbon emission impacts/benefits from the wood harvested for different products and applications as a substitution for potentially higher-GHG-emitting activities outside the forest system boundary, such as the use of concrete and steel in construction. The potential substitution calculator built into the Excel workbook uses lookup tables to estimate the average amount of potential GHG emission reductions through the substitution by HWPs from the current year's harvest.

When landowners conduct forestry operations, they often cut trees. In some cases, they cut all or nearly all trees in a stand; in others they cut only specific species, sizes, or combinations of trees. During harvest operations, trees are delimbed before or after skidding to landings, stacked, and then loaded onto trucks/trains for transport to wood processing facilities, where they are used as either sawlogs or pulpwood. Fuelwood is often taken to homes or retail operations. Some cut trees and associated slash remain in the forest after harvest.

To understand the net environmental impact of HWPs, one needs a clear understanding of the emissions associated with production of the wood products, along with their longevity across space and time (see figure 5-2). The production approach aids in understanding carbon storage and the longevity of storage. The longer the biogenic carbon in HWPs stays in a sequestered form, the more significant are the environmental benefits associated with the wood product under consideration (Lippke et al., 2011; Ganguly et al., 2020). However, these biogenic carbon storage benefits need to be compared against the fossil emissions associated with the harvest and manufacturing of these wood products, which can vary significantly among the wood products (Sathre and O'Connor, 2010; Ganguly et al., 2020). The LCA approach discussed here quantifies the holistic fossil fuel emissions during the harvesting, transportation, and manufacturing processes.

It is important to understand how the types of woody material left behind after harvesting affect the two HWP approaches. Cut trees left on site transition from the live standing ecosystem pool to the dead and downed pool, with potential transfer to the soil carbon pool as they decay; most stored carbon in these pools is eventually emitted to the atmosphere over time. Likewise, when loggers harvest a tree, they often leave some parts of it on site, including tops, branches, stump, roots, and sometimes bark. Landowners/foresters are advised to manage this woody material (biomass) to comply with fuel management regulations often established by jurisdictions (e.g., towns, counties, or the State) or by State Foresters. Foresters often pile the remaining woody materials and allow them to dry out before burning them without energy capture when wildfire is not a threat. In many cases foresters also conduct a prescribed fire at the harvest site to reduce dangerous fuel loads and to prepare the site for reforestation.

An approach to quantify the emissions associated with this woody material left on site postharvest is provided in section 5.2.1 (equation 5-3)(and is included as an output in the Excel workbook in the "Forest Management & HWP Results" tab in the green "Ecosystem Carbon Impacts" area of the tab).

Central to dealing with wood products in carbon emission inventories is recognition that when a forest is harvested, all of the sequestered carbon is not immediately released to the atmosphere. Some is released across century-long time scales. Some will be retained in wood products and in landfills and released to the atmosphere mainly as CO_2 but also as CH_4 over time (this guidance does not include associated methane emissions). Some carbon will be retained in perpetuity in landfills.[8] Once logs arrive at processing facilities, there are four general stages for the loss of carbon from wood products (Skog, 2001):

1. Processing roundwood to produce primary wood products.
2. Fabricating primary wood products into end uses.
3. Discarding products in use over time, with some burned, recycled, sent to landfills, or taken to secondary uses including recycling which can extend the carbon-in-use lifetime.
4. Decaying over time in landfills.

Other portions of this chapter discuss the amount of wood carbon that is released as CO_2 during the three processing stages (i.e., roundwood to primary products, primary products to finished products, and disposition of products at the end of their useful lives). This section deals with the amount of carbon that is released over time, up to decades and centuries, as products in use and products in landfills are burned or otherwise oxidized to CO_2.

Note that accounting for CO_2 emissions over time can be very different at a national or regional level than at the level of a smaller entity (e.g., Stockmann et al., 2012). For example, Skog and Nicholson (2000) estimate at the national level how the stock of carbon in wood products has evolved over the years and accumulated over time—tracking inputs to and outputs from carbon pools during each accounting year. Smaller-entity accounting deals with the anticipated decay of products and the release of carbon over time from a single harvest event or projection.

5.2.2.1 Description of Methods

This section describes the main approaches that entities and researchers currently use to quantify carbon storage and GHG emissions from HWPs: the production approach and the LCA approach. Given the complexity of available methods, tools, and models for quantifying carbon storage and other GHG impacts of HWPs, this section provides Level 1 versions of these approaches, though existing tools are referenced where more accurate estimates could be rendered. Level 1 approaches rely on the accompanying Excel workbook to combine built-in calculators with preprocessed values in lookup tables with basic user inputs to render region- and forest-type-specific values for the amount of carbon stored in products in use and in landfills and associated emissions.

Outputs from this section can be combined with the outputs from section 5.2.1 (converted from per area to total storage and emissions estimates) to develop a more complete understanding of GHG fluxes from forest management activities. The Excel workbook demonstrates how outputs from ecosystem and HWP modeling are combined, where all wood removed for wood products is converted into emissions or storage. Storage in HWP represents a transfer within the forest sector from ecosystem pools to HWP pools (both products in use and SWDS). Emissions include logging residues and bark (assumed to be immediately emitted from the ecosystem pools), emissions via processing in the year of harvest, and discarded product emissions (including burning and partial decay in landfills, which are all considered HWP emissions).

This method estimates carbon additions to the stock of HWPs from trees forest landowners harvest or when they have harvested or are contemplating harvest. The accounting framework used to track HWP carbon is similar to the framework that the UN reporting nations (including the United

[8] Dumps were not considered for the discarded wood products as the latest EPA waste reduction model (WARM) data suggests HWPs are no longer disposed of in dumps.

States) use to report national-level annual changes in HWP carbon stocks under the United Nations Framework Convention on Climate Change (UNFCCC).

The national accounting framework and these methods adopt the production approach: (1) tracking carbon in wood that was harvested in the United States (IPCC, 2006, 2019); (2) providing estimates that track wood carbon held in products, even if the products are exported to other countries; and (3) estimating the overall stocks and annual carbon additions to and removals from the stock of carbon stored in wood products in use and in landfills.

Note that use of the production approach to accounting is not an LCA that could evaluate the total potential environmental impacts of a product (or services) through its entire life cycle (an attributional LCA) and how environmental impacts change if increased wood burning or increased use of wood products to offset more fossil fuel emissions and emissions from making nonwood products over time (a consequential LCA; see appendix 5-B.2.3). The estimates of annual change in carbon in HWPs are not intended to indicate the total impact on GHG levels in the atmosphere of using HWPs (including use of wood for energy), nor are they intended to indicate that the emission to the atmosphere took place in the United States vs. other countries where products were exported. They are intended to model subnational entity carbon storage, essentially mirroring national-level UNFCCC reporting methodologies at a smaller scale.

The production approach acknowledges that harvesting of forests does not immediately release all the forest carbon to the atmosphere; the approach counts only the biogenic carbon change (stocks and emissions) for the HWP pool to allow annual carbon changes in HWPs to be deducted from or added to ecosystem changes; as a result, it is clear what happens in both the ecosystem and HWP pools. However, while the IPCC reporting keeps these separate—so there will be no omission or double-counting of sequestration or emissions to the atmosphere—these guidelines take the additional step of combining the estimates to demonstrate how harvesting simultaneously impacts both pools by transferring some carbon from ecosystem pools to HWP inputs.

In the national accounting framework, the annual emissions from wood energy are accounted for as emissions with energy capture. The remainder of energy emissions occur in other sectors. IPCC does not explicitly quantify the displacement of nonwood energy options when fuelwood and harvested wood products in use are disposed by burning with energy capture (i.e., wood energy). However, as part of the modeling approach in this chapter, the annual HWP emission estimates from wood energy, which are part of the aggregated annual change in forest (ecosystem plus HWP) carbon pools, are brought into a different potential substitution calculator that shows the amount of emissions displacement when wood burning displaces four common heating fuels. So, while wood energy displacement is not included in the production approach here, to ensure there is no omission or double counting of sequestration or emissions to the atmosphere, which user is instead provided potential substitution estimates to consider the impacts HWP wood energy has on the energy, manufacturing, and waste sectors.

Level 1: Production Approach

The Excel workbook combines user-provided activity data with built in calculators that estimate the carbon HWP stocks for the “Basic projection under fm, with harvest,” “Harvest,” and “Extended rotation” forest management activities. There are three calculators:

- The growing stock calculator
- The harvested wood storage calculator (abbreviated to “harvest carbon calculator” in this chapter)

- The potential substitution calculator

They work together to render results that are ultimately presented in the "Forest Management & HWP Results" tab of the Excel workbook.

Table 5-7 describes the required data inputs to apply the Level 1 production approach, as well as some caveats.

Table 5-7. HWP User Data for the Accompanying Excel Workbook

Data Input	Description/How Data Are Sourced/Relevance	Required?
Type of forest management treatment applied	Select one of the various types of forest management treatment to model. Note that the "harvest" scenario will not include quantified results for the forest management practices, as harvest is assumed to occur immediately after time 0. Harvest outputs are combined with the harvest carbon calculator outputs.	Yes
Area subject to management activity or area of stratum	Harvest area (either as hectares or acres). This is used to produce an estimated default growing stock value. Alternatively, if known, harvest volume or weight of up to three different products can be entered using a range of units—MBF (thousand board feet), CCF (hundred cubic feet), green tons, dry tons.	Yes
Area units	Enter acres or hectares.	Yes
U.S. region	The broad geographic region in which the HWP activity takes place. See figure 5-4 for a map of how the geographic regions are delineated.	Yes
Forest type group	Enter the forest type that best matches the forest stand (not the species of wood cut). Choose "unknown" if the forest type is not known.	Yes, if harvest volumes are not known
Planted or natural forest origin	Select whether the forest was planted or of natural origin. Choose "unknown" if the stand origin is not known.	Yes, if harvest volumes are not known

Data Input	Description/How Data Are Sourced/Relevance	Required?
Age class	Enter estimated age class of the stand (in 20-year classes up to 100-plus). Choose “unknown” if the age class is not known.	Yes, if harvest volumes are not known
Years until harvest	For forest management treatments that have a harvest, enter the years from now until harvest under the baseline (0–50, in 5-year classes up to 50). For extended rotation forest management treatments that have a harvest, enter the years until harvest under extended rotation (0–50, in 5-year classes up to 50).	Yes, if extended rotation
Harvest volume known	If the amount harvested, or to be harvested, is known, choose “yes.” This option bypasses the growing stock calculator.	No
Percent of the “area subject to management activity” to be harvested	If the entire “area subject to management activity” will not be harvested, enter the estimated percentage that will be harvested. For extended rotation activities that are assumed to be done in even-aged stands, this value defaults to 100 percent.	Yes
Harvest amount	Enter the numerical harvest value for up to three products.	Yes, if user-defined harvest data
Units	Enter the appropriate total or per area units.	Yes, if user- defined harvest data
Wood type	Enter “softwood,” “hardwood,” or “unknown” for up to three products.	No
Timber product	Enter the timber product type as sawlogs, pulpwood, or fuelwood. Choose “unknown” if the timber product type is not known.	No
Harvest fuelwood	Enter known fuelwood data. Use the default for any fuelwood for which data are unknown. Choose “no” if fuelwood was not part of the harvest amount.	No

Data Input	Description/How Data Are Sourced/Relevance	Required?
Fuelwood addition	Yes (default) or no to adding fuelwood to sawlog and/or pulpwood harvest amounts, based on what was removed from the forest.	No

Box 5-8. Key Definitions From Johnson (2001), Used by Smith et al. (2006) and in the Excel Workbook Calculators

Growing stock removals: The growing stock volume removed from poletimber and sawtimber trees in the timberland inventory. Includes volume removed for roundwood products, logging residues, and other removals.

- **Growing stock volume.** The cubic-foot volume of sound wood in growing stock trees with 5.0 inches dbh or larger, measured from a 1-foot stump to a minimum 4.0-inch top diameter of the central stem (outside bark).
- **Logging residues.** The unused merchantable portion of growing stock trees cut or destroyed during logging.
- **Sawtimber-size trees.** Softwoods 9.0 inches dbh and larger; hardwoods 11.0 inches dbh and larger.
- **Poletimber-size trees.** Softwoods 5.0 to 8.9 inches dbh; hardwoods 5.0 to 10.9 inches dbh.

Nongrowing stock sources: The net volume removed from the nongrowing stock portions of poletimber and sawtimber trees (stumps, tops, limbs, cull sections of central stem) and from any portion of a rough, rotten, sapling, dead, or non-forest tree.

Sawtimber volume: Growing stock volume in the sawlog portion of sawtimber-sized trees in board feet (international ¼-inch rule).

Pulpwood: A roundwood product that will be reduced to individual wood fibers by chemical or mechanical means. The fibers are used to make a broad generic group of pulp products that includes paper products and other engineered wood composites.

Fuelwood production: The volume of roundwood harvested to produce some form of energy (e.g., heat, steam) in residential, industrial, or institutional settings or public utilities; does not include derivatives of sawlogs or pulpwood used as fuel, called “fuel and other emissions primary products.”

Growing Stock Calculator

The growing stock calculator applies user inputs to query the FIADB (Burrill et al., 2021) and Smith et al. (2006) tables and ultimately estimates the harvest volumes by roundwood product types.

To use the calculator, enter data or select from dropdown menus in the “User Data Entry” tab of the Excel workbook.

1. Enter basic inputs:
    a. Enter the type of forest management treatment applied (options that will generate HWP results from growing stock are “Basic project under fm, with harvest,” “Harvest,” and “Extended rotation.”
    b. Enter an estimate of harvest area and choose units (acres or hectares).

c. Select U.S. region, forest type group, planted or natural forest stand origin, and age class.

2. Enter silviculture and harvesting inputs:
   a. Enter how many years from now until harvest.
   b. Enter "Yes" or "No" to the question, "Do you know what your harvest volume is?"

      If the volume is unknown, the growing stock calculator applies default estimates of growing stock (rendered from the FIADB net medium and large commercial volume and adjusted with Smith et al., 2006, lookup tables). If the volume is known, first enter the percent of the area subject to management activity from 1 to 100 percent. This reduces the growing stock subject to harvest using a percent. This could represent a reduction in areal extent (e.g., cut 80 percent of the forest area, leaving some areas uncut) or in the intensity of the harvest (e.g., cut 50 percent of the growing stock in the entire area). This reduction is not applied for extended rotation harvest, which assumes 100 percent is cut at the year entered for extended harvest.

      Then enter harvest amounts for up to three products with totals or, with per-acre values, the type of wood to be cut and sent to processing (softwood or hardwood) and the timber product category (sawlogs, pulpwood, or fuelwood), if known. If wood type or harvest information is not known, choose "unknown" and the calculator will use regional averages. Providing more details will yield more accurate estimates. Ensure all data, including total acreage, are put into the correct locations and units. Units for volume include MBF, CCF, green tons, and dry tons or cords.

      While using data from the table specific to forest type can improve modeling accuracy, note that these tables assume certain ratios of logs would come from certain species mixes, which may not accurately reflect a given landowner's harvest from their growing stock.

      The workbook will use the estimates to determine the total CCF equivalent of harvested roundwood.
   c. Determine if default fuelwood values should be applied.
      i. If sawlog and pulpwood production is not expected, select "No."
      ii. If unknown or if fuelwood data were previously entered, select "Yes." This adds fuelwood based on ratios from table 5B-3, unless fuelwood is any of the three indicated products. The results are harvest projections for use in the harvest carbon calculator (described below). Note that harvest projections may be greater than growing stock data entered because (1) roundwood yield is greater than 1.0 for growing stock in some regions and wood types and (2) fuelwood is added by default to sawlog and pulpwood volumes using default factors.

The calculator estimates the associated harvest volumes by product types using five pieces of information available by region (Smith et al., 2006):

- Averages for fraction of growing stock that is softwood/hardwood.
- Fraction of growing stock that is sawtimber size (table 5B-2).
- Fraction of growing stock volume that is roundwood—i.e., ratio of roundwood growing stock removals to total growing stock removals (roundwood + logging residues) (table 5B-3).
- Ratio of roundwood volume (excluding fuelwood) to total roundwood growing stock volume (including fuelwood) (table 5B-3).

- Ratio of fuelwood volume, from both growing stock and nongrowing stock sources, to total roundwood growing stock volume (including fuelwood) (table 5B-3).

The Smith et al. (2006) tables referenced above are included in appendix 5-B.2.2.

Harvest Carbon Calculator

The harvest carbon calculator automatically brings in the results from the “User Data Entry” tab. Total harvest units are determined by multiplying the user entered acres or hectares by the units entered on a per-area basis. The calculators currently use a ratio of 4.97 board feet per cubic foot (Verrill et al., 2004; gross board foot per net cubic foot ratio from 455,832 trees), which translates to 2.01 CCF per MBF; this may be adjusted in future versions to account for region, species taper, size classes, etc.

For CCF volumes, no conversion is needed. Volumes entered with MBF are multiplied by the ratio of CCF per MBF. Weights entered as dry tons are divided by the specific gravities (Smith et al., 2006) that correspond to the wood type and forest type in each region, then multiplied by 62.4 pounds per cubic foot, divided by 100 to get pounds per CCF, and then divided by 2,000 to get a CCF per ton. The CCF per ton conversion is used to compute CCF equivalents. For green ton weights, the calculator uses the same approach but also multiplies the CCF per ton by the appropriate average dry log weight relative to wet log weight for softwood (0.49) or hardwood (0.55) (Forest Products Laboratory, 2021).

The harvest carbon calculator relies on different proportions for sawlogs and pulpwood from table D6 of Smith et al. (2006) (table 5B-4) to allocate harvested wood in CCF equivalents into the full set of primary products in CCF units, using primary product ratios. For example, in the first row of table 5B-4, 0.391 of softwood sawlogs in the Northeast become softwood lumber, 0.004 become softwood plywood, etc. Note that 0.431 become fuel and other; across all rows, substantial portions of logs are converted to this coproduct, some of which is burned at the mill site to reduce energy needs to process the primary products. These portions are represented in the final column of table 5B-4 as “Fuel and Other Emissions,” which is emitted at year 0—in other words, the year of harvest.

Fuelwood can be entered by volume or weight, or the default calculator will use table 5B-3’s ratios of fuelwood to growing stock volume that is roundwood to estimate fuelwood using regional averages (ranging from 0.019 to 3.165) relative to the entered sawlog/pulpwood harvest or what the calculator derived from growing stock. Fuelwood is assumed to be burned with energy capture at the year of harvest, so it does not actually enter the products-in-use subpool; however, it is included in HWP emission estimates at year 0.

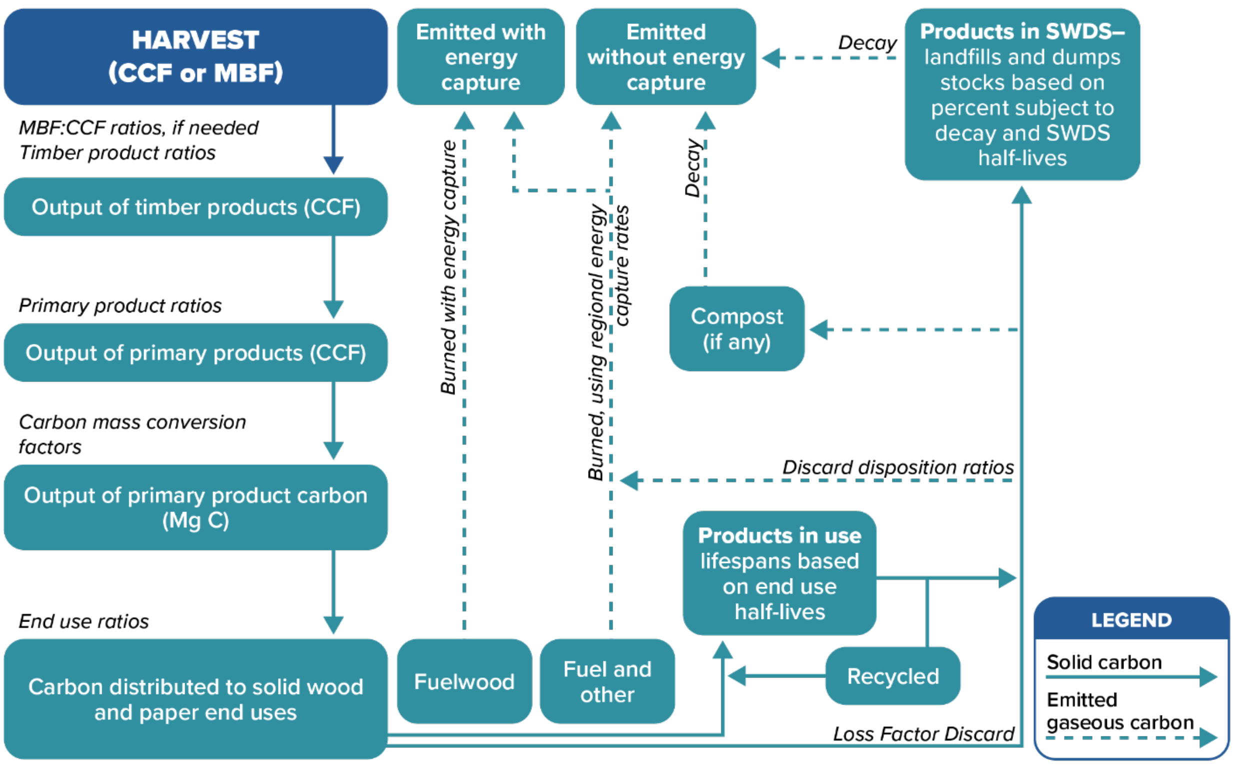
The calculator performs a series of conversions which differ slightly depending on if the inputs are softwood or hardwood and by forest type, by region. The calculator converts the CCF allocated to each primary product and coproducts into carbon mass by:

1. Accounting for density of wood relative to water using specific gravities for hardwood and softwood in each regions’ forest type group
2. Converting 1 cubic foot of dry wood to pounds by multiplying density by 62.4 pounds per cubic foot
3. Dividing pounds into tons, then
4. Multiplying the dry CCF with the IPCC-recommended carbon mass relative to dry wood mass (0.5)

5. Converting from U.S. tons to metric tons[9]
6. Multiplying this weight by 100 to convert a single cubic foot to CCF

The result is the metric tons or megagrams (Mg) of carbon mass found in the CCF for each primary product and coproduct.

At this point the calculator also estimates bark from sawlogs, pulpwood, and fuelwood. Carbon contained in bark is tracked but not reported as part of HWP stocks or emissions, following 2019 IPCC guidelines for HWP feedstock (underbark) (Rüter and Lundblad, 2019). Emissions with energy capture for all bark are, however, recognized as part of the substitution calculator described below (emissions for bark burned without energy capture are not used in the energy substitution calculator).



Note: Fuelwood and Fuel and other are primary products.

Figure 5-5. Flowchart of HWP Conversions and Allocation and Disposition Ratios Used to Estimate Annual Storage and Emissions

[9] 1 U.S. ton = 0.907185 metric ton.

Then the calculator takes the primary products and distributes them to the full range of end uses using national proportions (e.g., softwood lumber for multifamily home construction), then disposes of 5 percent of each solid wood end use as loss during installation (U.S. EPA, 2018). Next, the calculator models product lifespans by applying decay functions built with the half-lives (see appendix 5-B.2.2 for more detail) appropriate for the range of end uses to show the portions retained in the products-in-use pool for year 0 and each of the first 100 years. Then the model distributes the end uses that leave the products-in-use pool each year (5-percent losses at year 0 for solid wood product and annual losses thereafter for both paper and solid wood products) using the latest (2018 data reported in 2020) EPA WARM (U.S. EPA, 2020b) estimates for three disposition categories: reuse, landfills, and burned (compost was zero for both paper and solid wood products in 2018).

To handle the burned portion of the disposed products in use, the calculator applies results from a formula combining three regional softwood or hardwood coefficients and the year since harvest when they were disposed of from Smith et al. (2006) table D7 (based on Birdsey, 1996, pages 1–25, appendixes 2–4) to calculate the portions of disposed end use products burned with and without energy capture. Emissions with energy capture for all HWPs are used in the substitution calculator as well.

Next, the calculator sets aside two percentages of landfilled wood waste (88 percent for solid wood end uses (U.S. EPA, 2020b, table 6-6) and 44 percent for paper end uses (Smith et al., 2006)) as permanent storage and applies first-order decay functions (with half-lives specifically representing anaerobic landfill decay for solid wood and paper landfilled lifespans—of 29 and 14.5 years, respectively (de Silva Alves et al., 2000; Freed and Mintz, 2003)) to the portions of landfilled wood products subject to decay (U.S. EPA, 2020b), to show the proportions retained in the SWDS pool for year 0 and the next 100 years.

Subtracting the sum of these two portions from 1.0 results in the biogenic emissions for each year. Putting this all together reveals the annual stocks and stock changes, also called flux, a complete picture of storage and emissions through time. The calculator results show negative signs for sequestration in the ecosystem and positive numbers for movement between ecosystem and HWP storage subpools of the forest sector carbon. The forest sector stock change or flux is the net ecosystem exchange, including marginal sequestration from extended rotations when applicable, and logging residue and bark emissions, minus harvest, plus the change in HWP stocks (products in use and SWDS). The following section provides more detail on these steps as well as an emerging alternative approach to this part of the modeling.

Displacement factors for potential substitution benefits in reducing GHG emissions in construction and energy sectors are presented later, in table 5-10. These numbers are reported separately because they are part of the LCA approach explained below but are mentioned here to show the relationship between the two modeling approaches.

Primary Product End Use and Landfill Decay Tables

For HWPs, the Excel workbook uses decay functions to document the rate at which the carbon moves from the products-in-use pool to disposition. Decay functions are mathematical expressions in which the existing pool diminishes at a rate proportional to its current value and/or its age. In the workbook, decay functions are used for two separate applications.

First, the workbook uses decay functions to represent the rate at which wood products in use complete their useful lives and transition to disposal or reuse. Table 5-8 shows half-life estimates from Smith et al. (2006) for some end use groups and more recent numbers derived by following Skog (2008) table 8 for residential half-lives—escalated by roughly 2 years for every 20 years since 1940—as well as the percent loss when placed in use.

Table 5-8. Half-Lives and Loss When Placed in Use for Primary Product End Uses

End Use or Product	Half-life in Years	Loss When Placed In Use
New Residential Construction		
Single family	87.8	0.05
Multifamily	53.7	0.05
Mobile homes	12.0	0.05
Residential Upkeep and Improvement	26.1	0.05
New Nonresidential Construction		
All ex. Railroads	67.0	0.05
Railroad ties	12.0	0.05
Railcar repair	12.0	0.05
Manufacturing		
Household furniture	30.0	0.05
Commercial furniture	30.0	0.05
Other products	12.0	0.05
Shipping		
Wooden containers	6.0	0.05
Pallets	6.0	0.05
Dunnage, etc.	6.0	0.05
Other Uses for Lumber and Panels	12.0	0.05
Miscellaneous Products	12.0	0.05
Solidwood Exports	12.0	0.05
Paper	2.5	0

Source: Smith et al., 2006; Skog, 2008 (adapted from information in table 8).

Second, the workbook uses a set of decay functions to determine the rate at which the solid waste in landfills decays over time and releases some of the biogenic carbon back to the atmosphere. When the rate of “decay” (i.e., the percent of carbon leaving the pool over any interval) is the same over equal intervals of time, the decay function takes the shape of an exponential curve. This pattern of exponential decay is widely used for modeling natural processes (like decay of wood in a landfill), but wood products leaving their functional life may follow a more complicated pattern. Appendix 5-A.3 discusses some potential patterns (i.e., distributions) that would represent the decay rates of various wood products under consideration.

Conventional exponential functions in table 5-B-5 and table 5-B-6 in appendix 5-B.2.2, and new chi-square functions (workbook default) in table 5-B-8 and table 5-B-9, reflect the total of all end use wood carbon in each primary product category in the products-in-use pool and the solid waste disposal pool (end-of-life portion) with fractions remaining for the subsequent 100 years. The calculator shows 1 minus the sum of these two fractions, or the remainder of the carbon, as being emitted through the combination of burning and decay by each year. In this way, the Excel workbook estimates HWP storage by adding the carbon masses for each primary product category multiplied by the fractions of each primary product remaining in end uses and SWDS each year, and then estimates emissions by any given year as 1 minus the combined fractions. See an example of the chi-square functions in box 5-9.

Box 5-9. Harvest Carbon Calculator Calculation Examples

Softwood Lumber

At year 10, table 5-B-8 shows 0.859 of softwood lumber remain in products in use; table 5-B-9 shows 0.112 of softwood lumber carbon originally placed in SWDS remains at year 10. Therefore 0.971 (= 0.859 + 0.112) of the carbon originally stored in softwood lumber in year 0 remains and 0.029 (= 1 − 0.971) has been emitted.

Looking at year 100, 0.134 of softwood lumber remains in products in use and 0.644 remains stored in SWDS. The remainder, 1 − (0.134 + 0.644) = 0.222, has been emitted.

Northeast Wood Pulp

Northeast wood pulp decays more quickly but also has high recycling rates: by year 10, 0.829402 remains, with 0.402 in products in use and 0.427 in SWDS. The remaining 0.171, 1 − (0.402 + 0.427), has been emitted.

Note that there are minor rounding differences for the fractions shown in this example.

Emission tallies start with all the fuelwood and the fuel and other emissions from year 0. Then, starting in year 1, the calculator takes the original carbon mass for each primary product category and multiplies it by 1 minus the combined fractions remaining. All of the products are then summed for a results summary. This is then converted to metric tons CO_2-eq by multiplying by 3.67 (or 44/12, the ratio of the molecular weights of CO_2 and carbon). Because the calculator models a single harvest event (not a multi-year harvest record) the total end use carbon remaining and the total of all wood removed from the forest that remains stored both decline over time.

When "fuel and other" coproduct biogenic emissions are combined with these annual biogenic emissions from the disposed solid wood burning and landfill decay to estimate cumulative emissions by the listed year there are large amounts shown in year 0—the year of initial processing—followed by smaller amounts in later years.

Summary results are presented as CO_2-eq in the "Forest Management & HWP Results" tab and detailed annual results are presented in the "Harvest Carbon Calculator" tab of the accompanying Excel workbook. The harvest carbon calculator shows three sets of results. The first are chi-square results by year in t CO_2-eq, then exponential results by year and chi-square results (Mg). All tables start with zero in rows for years after harvest in the calculator output table and contain as total products-in-use carbon (Mg), total SWDS carbon (Mg), total HWP carbon storage (Mg), annual HWP carbon stock change (flux in Mg), percent of installed end uses remaining stored, percent of harvest log carbon (underbark) remaining stored, coproduct biogenic fuel and other emissions year of processing (Mg), fuelwood emissions year of harvest (Mg), cumulative end use emissions carbon by this year (Mg), cumulative end use emissions by this year (t CO_2-eq), annual HWP emissions with energy capture (t CO_2-eq), annual HWP emissions without energy capture (t CO_2-eq),cumulative emissions by this year (t CO_2-eq), and percent of HWP carbon emitted by this year.

Bark is also computed on this tab, although it is listed separately because it is not considered HWP stock or emissions under current IPCC roundwood (underbark) feedstock definitions (Rüter and Lundblad, 2019). However, some wood processing facilities in the United States use bark for products such as landscaping materials or energy production (Marcille et al., 2020).

See appendix 5-B.2 for a full description of this chapter's novel approach to producing decay functions using chi-square functions to represent the lifespans for solid wood products and as displayed in the Excel workbook as default results. Users may choose to render results using the traditional exponential decay functions as well.

Level 1: LCA Approach

LCA Quantification of HWP Emissions (Cradle to Gate, From Forest to Product Manufacturing Gate)

The LCA method described in this chapter focuses on the fossil-based GHG emissions reported as CO_2-eq; it leaves out biogenic carbon, which is reported separately within the LCA framework following ISO 21930. It uses information derived from LCA studies that covered stages from raw material extraction to product manufacturing (cradle-to-gate), guided by the framework and guidelines from ISO 14040 and ISO 14044. An example of the LCA method can be found in section 5-B.2.3. Table 5-9 provides the GHG emission factor (in metric tons CO_2-eq/metric ton of product) of each HWP produced from forest lands, based on the U.S. LCA studies. (Note that mass product units are all on a dry basis.) The values—averages for the United States and some U.S. regions—include fossil CO_2, all CH_4, and all N_2O emissions within the specified system boundary. The total fossil-based GHG emissions for HWP manufacturing, from cradle to manufacturing gate, can be quantified by multiplying the HWPs' mass with the LCA-determined emission factors summarized in table 5-9. The LCA-quantified HWP fossil emissions are used to derive the displacement factors for substitution benefits, as described in the following section.

Table 5-9. Life Cycle GHG Emissions for Cradle-To-Gate Manufacturing of HWPs (Metric Tons CO_2-eq/Metric Ton of HWP Produced)

HWP	U.S. Average	Pacific Northwest	Southeast	Inland Northwest	Northeast–North Central	Study References
Softwood lumber	0.161	0.131	0.167	0.241	0.108	Puettmann, 2020a, 2020b, 2020c, 2020d
Hardwood lumber	0.273	ND	ND	ND	0.273	Hubbard et al., 2020
Plywood	0.476	0.395	0.558	ND	ND	Puettmann, 2020e, 2020f
Oriented strandboard	0.391	ND	ND	ND	0.391	Puettmann, 2020g
Non-structural panels[a]	0.742	ND	ND	ND	ND	Puettmann and Salazar, 2019; Puettmann and Salazar, 2018; Puettmann et al., 2016
Other industrial products[b]	0.272	ND	ND	ND	ND	Alanya-Rosenbaum and Bergman, 2020

ND = No data.

[a] Non-structural panels include three HWPs (particleboard, medium-density fiberboard, and hardboard). The GHG emissions value is a weighted average of the three.

[b] GHG emissions for wood pallets were used as a reference for other industrial products.

Avoided Emissions or Emission Reductions from HWP Substitution

LCA-quantified GHG emissions for wood products can be compared to emissions for functionally equivalent nonwood products (e.g., concrete and steel) to find out the possible maximum substitution benefits. Similar comparisons can be made between wood-based energy and fossil-based energy (e.g., coal, heating oil, natural gas). Because the life cycle GHG emissions associated with wood product manufacturing are generally lower than emissions for functionally equivalent nonwood materials, substituting wood for high-emitting nonwood materials will result in reduced GHG emissions.

A displacement factor (DF) measures the GHG emissions avoided when wood is used instead of nonwood fossil or petroleum-based material. DFs are estimated by comparing the total GHG emission differences between wood and nonwood products and divided by the corresponding carbon content. The expression is shown in equation 5-7 (Sathre and O'Connor, 2010):

Equation 5-7: DF for HWP GHG Emission Reductions

$$DF = \frac{GHG_{\mathbf{nonwood}} - GHG_{\mathbf{wood}}}{Carbon_{\mathbf{wood}} - Carbon_{\mathbf{nonwood}}}$$

Where:

DF	=	displacement factor (dimensionless)
GHG_{wood},	=	GHG emissions for wood, obtained from LCA studies (CO_2-eq)
$GHG_{nonwood}$	=	GHG emissions for nonwood alternatives, obtained from LCA studies (CO_2-eq)
$Carbon_{wood}$,	=	amounts of carbon contained in wood material (CO_2-eq)
$Carbon_{nonwood}$	=	0, unless the nonwood material contains biogenic carbon (CO_2-eq)

Note that the denominator in equation 5-7 requires carbon contained in the wood to be expressed as CO_2-eq. Since the LCA results for HWPs provided GHG emissions per metric ton of the product (as shown in table 5-9), the numerator (GHG emissions) must be presented as CO_2-eq emissions from the CO_2-eq contained in the wood. Table 5-10 presents these converted values based on the average density and moisture levels of the HWPs for all the regions. Table 5-10 provides only rough estimates and examples for displacement factors based on the limited research studies. Gaps in this area have been identified and are expected to be addressed with future, refined estimates.

For the estimation of DFs, this chapter draws on data from various studies (Xu et al., 2021; Leturcq, 2020; Krajnc, 2015; Bergman et al., 2014). Data were insufficient to estimate DFs for some HWPs; in those cases, this chapter uses averaged DFs from published meta-analyses (Leskinen et al., 2018).

Landowners can interpret the DF as an estimated potential savings in GHG emissions (i.e., reduction benefit) from substituting wood products and woody biomass energy for functionally equivalent nonwood products and fossil/non-renewable energy sources (table 5-10 and table 5-11).

Table 5-10. DFs for Material Substitution: HWPs Against Nonwood Products

HWP	Functionally Equivalent Nonwood Product	DF (Metric Tons CO_2-eq Avoided/Metric Ton CO_2-eq in HWP Used)	Reference
Softwood lumber	One steel stud[a]	0.99	Adapted from Bergman et al. (2014)
Hardwood lumber	One steel door[a]	2.29	Adapted from Bergman et al. (2014)
Plywood	Structural construction materials	1.3	Leskinen et al. (2018)
Oriented strandboard	Structural construction materials	1.3	Leskinen et al. (2018)
Other industrial products	Non-structural construction materials	1.6	Leskinen et al. (2018)
Other industrial products	Non-construction use	1.2	Leskinen et al. (2018)

[a] GHG emissions for the galvanized steel manufacturing process were used for steel studs and steel doors (source: Cai et al., 2022).

Table 5-11. DFs for Energy Substitution: Woody Biomass Associated With HWP Harvest, Transportation, and Production Against Nonwood Fossil Energy and Heating Sources

HWP	DF (Metric Tons CO_2-eq Avoided/Metric Ton CO_2-eq in HWP Used)
Electricity[a]	
Mill residues	0.270[c]
Logging residues	0.267[c]
Softwood pulp	0.261[c]
Heat (Wood Fuel)[b]	
Coal	0.68[d]
Oil	0.57[d]
Natural gas	0.45[d]

[a] Emissions for grid-based electricity were taken from U.S. EPA (2018a) eGRID using the national average profile.

[b] The calorific value of wood chips at 30 percent moisture content (12.2 megajoules/kg) was used (Krajnc, 2015).

[c] DFs when the woody biomass generated electricity to displace the U.S. grid-based electricity (mix of fossil and renewable sources).

[d] DFs when wood fuel generated heat to displace the fossil fuel (coal, oil or natural gas) generated heat.

Calculation of Potential Substitution Benefits from the Construction and Energy Sectors

For construction product substitution benefits, estimates made using the harvest carbon calculator for primary product carbon masses can be used in the potential substitution calculator. The calculator takes the appropriate masses of HWPs produced, converts them to CO_2-eq (by multiplying metric tons by the molecular weight conversion, 44/12 or 3.67), and multiplies the result by the DFs shown in table 5-10. The result gives the landowner a sense of GHG emissions that could be avoided if the full mass of the HWP produced from their land is considered to substitute for those functionally equivalent nonwood products in construction or other use.

For energy substitution benefits, estimates made using the harvest carbon calculator for the limited set of fuelwood emissions (CO_2-eq), and bark emissions (CO_2-eq) at the year of harvesting and processing (year 0) can be multiplied by the DFs in table 5-11 for different options in substitution benefits:

- Most (~80 percent) of the fuel and other (hog fuel and other mill residue) coproduct is already captured in the DF calculations for the wood products and is therefore shown in the product portion of the potential substitution calculator.
- Energy from burning woody biomass is used to substitute for electricity; the electricity values shown in table 5-11 do reflect renewables as part of the production portfolio.
- Heat generated from burning wood fuel substitutes for three fossil-based heating sources: anthracite coal, heating oil, and natural gas.

The calculator's results represent the GHG emissions that could be avoided when woody biomass associated with HWPs produced from the landowner's land is substituted for fossil fuel heating or electricity use. (In other words, the potential substitution calculator makes a big assumption—that all wood used in construction and burned with energy capture in year 0 substitutes for nonwood alternatives.)

5.2.2.2 Activity Data

Because entities may have many different types of information to describe the amount of wood harvested to estimate carbon stocks in HWP, the Excel workbook accepts a range of activity data:

- Growing stock cutting (described in the "Growing Stock Calculator" section).
- Harvest volume estimates (hundred cubic feet or thousand board feet volume, weights in green or dry tons).
- Volume conversions.
- Volume to carbon conversions.
- Loss factors.

5.2.2.3 Limitations and Uncertainty

Limitations

<u>Level 1: Production Approach</u>

The starting point for estimating carbon storage is estimating carbon content by converting from the weight(s) or volume(s) growing or harvested. The first step is entering either growing stock or harvest volumes (or projections). This might seem like basic information, but landowners have a wide range of access to it. Something as simple as log scale vs. lumber scale, or total volume compared to sawlog or merchantable volume, can create confusion and lead to incorrect estimates. Landowners should ask questions, when they survey (cruise) or sell timber products, that will lead to known, high-quality inputs.

There are many averages and conversion factors strung together to complete HWP production approach modeling. Many of these conversion factors (e.g., MBF/CCF) are contingent on variables beyond the scope of the Level 1 approach. For example, species mixes, tree dimensions, sawmill minimum sizes, etc., can influence the conversion factors. Entities with a need for accuracy or precision beyond regional average single conversion factors may wish to model with other more advanced tools, conduct uncertainty analyses, or cite existing uncertainty analyses from various authors.

Emission estimates shown in section 5.2.2 are restricted to CO_2—they do not include CH_4 or other GHG emissions—but are nevertheless presented in units of metric tons CO_2-eq. The IPCC guidelines (2006) for national estimates of CO_2 GHG emissions released from wood products in landfills are not included in the emissions from the waste sector but are included in the HWP pool of the AFOLU sector. On the other hand, emissions of CH_4 from landfills are included in the waste sector and therefore not included in HWP pool. IPCC (2006) explains: "The outflow and oxidation data of HWP are much more uncertain than the input data and are likely to be underestimated, as a result a significant part of decay would not be identified and net additions to carbon held in HWP would be overestimated." Future versions of these guidelines may address the topic of HWP landfill methane production from an "entity perspective" when such calculations can be determined with more certainty.

A more detailed discussion of data sources and limitations for several conversion factors, wood utilization parameters, discard pathways, and decay rates is offered in Lucey et al. (in review).

Level 1: LCA Approach

The Level 1 DFs for HWPs in construction use are averages from data referenced in published meta-analysis reports (Hurmekoski et al., 2021; Leskinen et al., 2018; Sathre and O'Connor, 2010). Otherwise, the two specific substitution paths, defined for softwood lumber and hardwood lumber as shown in table 5-10, and the associated individual DFs were calculated for this chapter based on the available LCAs and substitution data. Additional individualized DFs are needed for better quantification of substitution benefits from HWP.

Also, the substitution calculator's estimates do not include emissions when primary product end use HWPs are disposed of by burning (about 16 percent of solid wood products and 6 percent of paper), which is reduced with energy capture ratios to just the portion burned with energy capture. This is because the system boundary for the provided DFs is cradle to gate and does not include use or disposal stages.

Regarding DF and substitution benefit, the LCA literature provides strong evidence that most wood-based products are associated with lower fossil-based emissions over the product's life cycle compared to functionally equivalent nonwood-based substitutes. A DF quantifies the reduction in emissions per unit of wood used in specific end-use applications. DF values also factor in the efficiency of biomass in decreasing GHG emissions, as they go down with increased wood use for the same amount of GHG emission reduction. This guidance calculates the substitution benefit for various wood product groups (softwood lumber, hardwood plywood, etc.) using a weighted average of various end-use-specific DF values. These substitution benefit values could be used to estimate the change in emissions compared to the current baseline practices.

Regarding interpretation of substitution benefits**,** the material substitution numbers used in this guidance can be used to analyze micro-level substitutions by examining the marginal change between individual products or processes. The substitution benefit numbers can also be used to analyze the meso-level substitutions by examining the marginal structural changes in society's production and consumption patterns between industries or sectors of the economy (Gustavsson and Sathre, 2011). These numbers are not intended for macro-level estimates, which would require a better understanding of the macroeconomic and landscape implications of large-scale wood-based (or nonwood-based) substitutions. In such macro-level substitution scenarios, direct and indirect market responses, and the interdependencies between the various industrial sectors, must be analyzed to understand the net impacts on the resultant GHG flows.

Uncertainty

Strict adherence to the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report (U.S. EPA, 2020a) would require Monte Carlo simulations with assumptions and probability distributions regarding uncertainty for HWP specified for key variables including:

- Fractions of sawlogs and pulpwood going to various primary products
- Fractions of primary products going to various end uses
- Half-lives for primary product end uses
- Rate at which products are discarded from each end use
- Fraction of discarded wood or paper that goes to landfills
- Fraction of wood or paper sent to landfills that is subject to decay
- Rate of decay in landfills of degradable wood/paper carbon

Such simulations are beyond the scope of the Level 1 calculators and are better handled with more advanced models.

For context, Stockmann et al. (2012) conducted an uncertainty analysis for their carbon storage estimates in the Northern Region of the National Forest System. They used triangular distributions with 18 variables; expert opinion determined variable distributions, which generally narrowed in more recent years. They found a 90-percent confidence interval of -26.7 to 31.2 percent difference from the mean. That uncertainty was for more than 100 years of harvest data, so uncertainty for a single year—such as that modeled with the tool described in this section—would likely be far less.

More research is needed to improve differentiation of the various rates at which solid wood products are discarded from uses such as pallets, railroad, railcars, and furniture. These are currently grouped into one category; differentiating them would refine estimates of average carbon stored when a landowner knows which primary wood products are made from the wood that is harvested from their land. Alternate, empirically verified curves for discard rates from end uses, particularly discards from housing, could improve estimates of average carbon stored.

Variability in the DFs of wood to nonwood product substitution and biomass energy to fossil energy substitution is unknown but expected to be large. Note that, for instance, the DF of 0.99 for softwood lumber was an average of 0.85 from the Southeast and 1.13 in the Northeast–North Central region. This is because of the difference in the LCA-quantified GHG emissions of lumber production in these two regions: 0.168 and 0.108 kg CO_2-eq per metric ton of softwood lumber, respectively, in the two regions. Having more data points from future studies in this field would help in estimating DFs (regional and U.S. average) with reduced uncertainties.

5.2.3 Wildfire and Prescribed Fire

Method for Estimating Emissions From Wildfire and Prescribed Fire

- There are two Levels available for this sector, depending on data availability and user resources.
- For Level 1, use the Excel workbook with lookup tables developed by combining FIADB data on stand structure and surface fuel loading with the Forest Vegetation Simulator with the Fire and Fuels Extension (FFE-FVS).
- For Level 3, use FFE-FVS, FOFEM, or Fuel and Fire Tools (FFT) to produce custom modeled fire and emission scenarios.

5.2.3.1 Description of Method

Wildland fires produce direct and indirect carbon emissions. The direct emissions are instantaneous GHGs produced from the combustion of live and dead fuels including foliage, litter, duff, down dead wood (DDW), and dead tree boles (central stem of a tree). The mass of emissions produced is directly proportional to the mass of fuel consumed by fire. The amount of combustion and emissions varies based on the quantity and arrangement of live and dead fuel on a site, forest type, fuel moisture, and weather, all of which influence intensity (Finney et al., 2003; Loehman et al., 2014; Prichard et al., 2022; Urbanski et al., 2022). Combustion releases more carbon-containing gases and particles when fuel conditions are dry, due to increased consumption of large woody fuels and duff. Surface fuels such as dead leaves, grasses, and needles are largely consumed during most fires even during relatively moist conditions. When fuel and weather conditions are extreme, surface fires can transition to the crowns, burning both live and dead foliage and fine branches on trees (Loehman et al., 2014); the consumption of live tree boles and large branches is typically minimal, though, even during crown fires (Johnson, 1992).

This section offers two Levels for estimating emissions from wildfire and prescribed fire.

Level 1 Approach

In the Level 1 approach, the Excel workbook combines activity data (i.e., an estimate of the area burned or to be burned) with an emission factor calculated based on fire severity, region (using the regions shown in figure 5-4), forest type (based on the table in table 5-B-11), flame length, and fuel moisture. Enter each into the Excel workbook.

The Excel workbook produces estimates of emissions for three fire activity scenarios, described in table 5-12: high-severity wildfire, moderate-severity wildfire, and low-severity wildfire/prescribed burn. To produce estimates for mixed-severity burns, distribute the burned area across the fire activity scenarios. Because many plots fall into each bin of fire severity, forest type, and region, the approach summarizes emissions to the 25th, 50th (median), and 75th percentiles.

Table 5-12. Fire Activity Scenarios

Fire Activity	Description
Low-severity wildfire/prescribed fire[a]	< 20% tree mortality
Moderate-severity wildfire	40–60% tree mortality
High-severity wildfire	>90% tree mortality

[a] Prescribed fires can be of varying severities, including high-severity crown fire, but many resemble the low-severity scenario.

Fire severity corresponds to the percentage of tree mortality (quantified with basal area per hectare), as shown in figure 5-6.

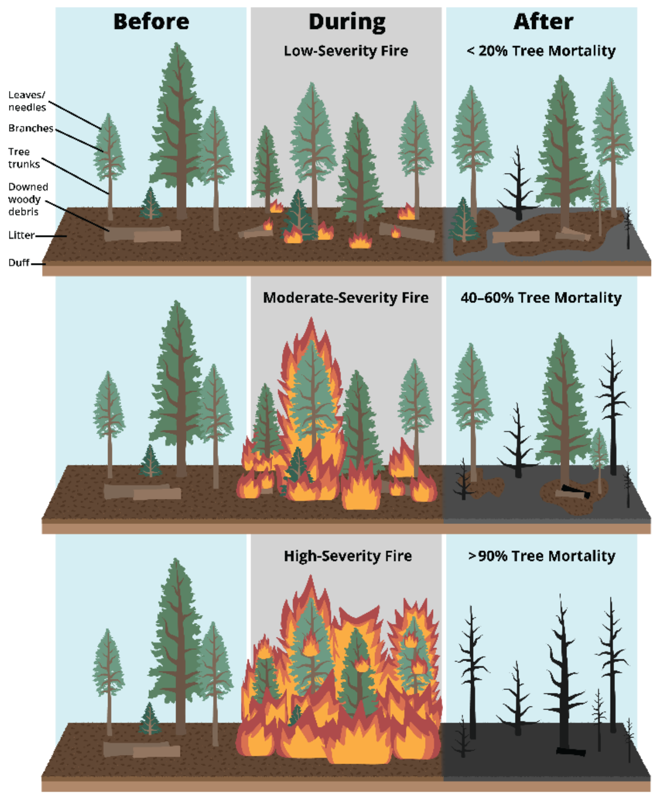


Figure 5-6. Diagram of the Three Fire Severity Levels for Which Level 1 Results Are Available

To estimate fire-induced GHG emissions and changes to carbon pools and vegetation under each of the scenarios described in table 5-12 for each forest type by region, the Level 1 approach combines:

- Estimates of initial (prefire) forest stand structure (species, size, number, and health of trees) and surface fuel loadings (DDW, litter, and duff), for different forest types and regions, from field measurements made by the FIA program.
- Simulations of fire under different flame lengths, fuel moistures, and weather conditions in FFE-FVS.
- FIA records the size (dbh and height of tree), status (live or dead), and species of each tree on its plots. FIA also measures litter and duff depth at eight points at each plot, as well as measuring DDW (e.g., branches and logs) along a set of transects; this information is stored in the DDW table (Burrill et al., 2018; USDA Forest Service, 2022b).

FVS is a forest growth model that simulates forest vegetation change in response to natural succession, disturbances, and management (Dixon, 2002); FFE simulates fuel dynamics, fire behavior, fuel consumption, and mortality due to fire (Rebain et al., 2021). FFE-FVS uses many of the same internal algorithms for estimating fuel consumption and emissions as the FOFEM model prescribed in the 2014 guidelines, as well as a similar tree mortality approach; unlike FOFEM, though, it can simulate stand, fuel, and carbon dynamics over time while also being able to incorporate FIADB (Burrill et al., 2021) plot data—that is, it is dynamically connected to contemporary forest resource information via FIA data. It is a powerful predictive tool, offering a more advanced means to simulate fire impacts than simpler algorithms such as those in the *2006 IPCC Guidelines for National GHG Inventories* (IPCC, 2006) while also enabling simulation of various management approaches (e.g., clear-cut vs. timber stand improvement activities). In totality, this approach facilitates connections among national databases, modeling/simulation tools, and region/forest type configurations while acknowledging much work remains in refining approaches to estimating probabilities of future fire occurrence, forest management activities, and fuel dynamics under global change scenarios.

FIA data from FVS-ready tables packaged with FIADB (Shaw and Gagnon, 2019) were used in FFE-FVS to establish prefire carbon pools and fuel loading for trees (live and dead), herbs and shrubs, woody fuels, litter, and duff (Crookston and Dixon, 2005) (see figure 5-1). FFE was then used to simulate immediate fire effects—tree mortality, fuel consumption, and changes in carbon pools resulting from three wildland fire scenarios (see table 5-12). GHG fire emissions are calculated as the product of fuel consumption from the FFE-FVS simulations and pollutant emission factors as described in appendix 5-B (see table 5B-12). Fuel consumption depends on fuel quantity, fuel properties (particle size, packing density, moisture content), weather, and fire behavior. The fraction of fuel consumed by fire can vary considerably across fuel strata (e.g., trees, litter, duff, and dead woody fuels; for example, a low-severity fire might consume 60 percent of the litter and 0 percent of the canopy fuel).

To determine the mortality levels of the fire severity scenarios, FFE simulations were run using a matrix of fire-related parameters (wind speed, fuel moisture, temperature, and burn patchiness). The mortality resulting from a given set of parameters can vary tremendously between forest stands. Region, forest type, and stand composition and structure are critical factors in stand mortality. Tree species and diameter are also important factors; for a given fire scenario, mortality may be highly variable across stands of the same forest type and region. Mortality simulation results were retained for creating estimates of GHG emissions and carbon pools (see table 5B-13).

FIA data from about 70,000 plots were processed with FFE-FVS to produce each of the fire severity scenarios. Because FVS is organized as a set of 20 regional variants, subsets of FIA plots were run using the variants in which they were located. FIA plots were attributed with FIA forest type and forest type group classifications (table 5B-11); the geographic regions depicted in figure 5-4 were assigned to FVS output by aggregating States and counties assigned to the regions. For the conterminous United States, over 350,000 combinations of region, forest type, and fire conditions were simulated. Appendix 5-B.3.2 provides more details on the simulation procedure.

Emissions of GHGs—including CO_2, N_2O, and CH_4—were calculated as the product of fuel consumption from the FFE-FVS simulations, using pollutant emission factors as described in chapter 2.

Estimates of fire effects and carbon were produced and aggregated into lookup tables based on forest type (table 5B-11), geographic region (figure 5-4), and fire severity (table 5-12):

- **FIRE table.** Immediate fire effects on the forest—biomass consumed, carbon emitted, carbon remaining, and GHG emissions.
- **CARBON table.** Prefire and immediate postfire carbon pool estimates.

The accompanying Excel workbook offers estimates of GHG emissions for the three fire severity scenarios based on user-provided information on area, region, and forest type. Figure 5-7 summarizes the method by which these estimates were produced.

See appendix 5-B.3.2 for details on the approach described above.

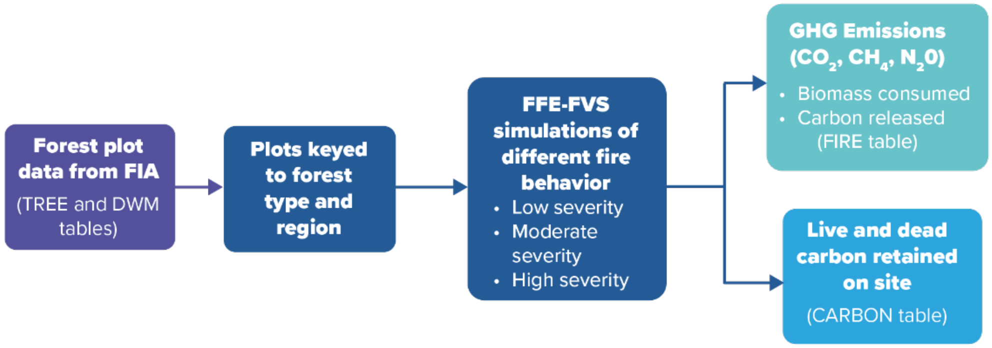


Figure 5-7. Diagram of the Wildfire Carbon Flux Method

Interpreting Results

The Excel workbook outputs present estimated emissions from fire according to the three scenarios in table 5-12. This approach is limited to immediate fire-induced GHG emissions and does not address postfire forest carbon fluxes such as the decay of fire-killed biomass. As a result, it is merely a potential starting point for assessing the forest carbon implications of fuel management treatments intended to improve forest health and reduce the risk of catastrophic wildfires.

These treatments can effectively reduce the severity of fires for a time, after which they may reduce the size of fires by reducing rates of spread and providing opportunities for fire suppression forces. However, their implications are complex—and the subject of ongoing research (Prichard et al., 2021; Thompson et al., 2017).

Level 3 Approach

For more advanced users, a number of options are available for estimating emissions from specific fire scenarios.

FFE-FVS (Rebain, 2010; Reinhardt and Crookston, 2003), used as part of the Level 1 approach, can also be used for custom model runs. FFE-FVS estimates tree mortality, fuel consumption, and emissions and simulates stand, fuel, and carbon dynamics over time. It is a powerful predictive tool, but using it for custom runs involves substantially more work in understanding the modeling framework, setting up runs, and preparing data.

Another option for advanced users is FOFEM (Reinhardt et al., 1997; Lutes, 2019), which is applicable nationally, has code that can be linked to or incorporated into other code, and defines inputs so that measured biomass can be entered or default values generated by vegetation type (USDA Forest Service, 2022d). FOFEM produces direct estimates of GHG CO_2 and CH_4, as well as estimates of fuel consumption by component, which can be used to determine residual fuel quantities for estimating subsequent decomposition. FOFEM can also be used to compute tree mortality in order to update estimates of live and dead biomass.

FFT, like FOFEM, can be used to directly compute emissions and fuel consumption from fire (USDA Forest Service, 2022e). FFT outputs include estimates of carbon stores for different fuelbeds, fire-induced carbon emissions, and fuel consumption. However, unlike FOFEM and FFE-FVS, FFT does not provide tree mortality estimates.

5.2.3.2 Activity Data

Activity data represent the area (in hectares or acres) in which the activity takes place—that is, the area burned.

5.2.3.3 Limitations and Uncertainty

Limitations

The methodology in this section does not quantify several aspects of carbon emissions and uptake by forest systems related to fire. It is limited to instantaneous emissions from fire and does not quantify postfire vegetation trajectories and decomposition. It also does not include GHG emissions associated with pile burns of forest residue and non-fire natural disturbances, though they are important sources of GHGs.

The methodology also cannot quantify "avoided emissions" from fuel treatments. These result from fires burning less area or burning at lower severities. Fuel treatments may yield a carbon benefit if they contribute to a reduction in the fire severity and resulting tree mortality of a future wildfire on the treatment site.

In the short term, fuel treatments result in carbon emissions, since they intentionally reduce live and dead carbon stocks (Ager et al., 2010). Outcomes for emissions and long-term landscape carbon stocks depend on many factors, including changes in the subsequent frequency, intensity, and rate of spread of fires; the growth response of treated stands in terms of future net sequestration; the amount of carbon emitted from fossil fuel use during the treatment (for transportation and machinery); and the fate of any harvested wood (i.e., furniture, building materials, or other products that can store carbon over long periods). To incorporate these, the method would need to encompass stochastic modeling of wildfire and trajectories of mortality and regrowth over time, as well as the fate of harvested wood. Future improvements to the methods presented in this section may provide a more direct path for evaluating the implications of contemporary fuel management strategies.

GHG Emissions From Pile Burns

This section does not address GHG emissions from pile burning. Forest management activities—regeneration harvests, salvage logging, hazard reduction treatments, restoration, and thinning treatments—and natural disturbances such as mountain pine beetle infestations and windstorm blowdowns create woody debris (often called "slash") and cull piles. This woody debris is commonly collected, by hand or mechanically, into piles for disposal via burning. These piles, which can exceed 50 cubic meters in volume, are allowed to dry for a year or more before they are burned. The combustion process of pile burns and the resultant emissions of GHGs and air pollutants—e.g., fine particulate matter, carbon monoxide, and volatile organic compounds (VOCs)—depend on many factors including the pile geometry, size distribution of woody debris, packing density, pile age, and moisture content (Hardy, 1998; Wright et al., 2009). Users interested in calculating emissions from pile burns are referred to FOFEM (Reinhardt et al., 1997; Lutes, 2019) and the Piled Fuels Biomass and Emissions Calculator (https://www.fs.usda.gov/pnw/tools/piled-fuels-biomass-and-emissions-calculator-tool; Wright, 2015).

Avoided Wildfire Emissions

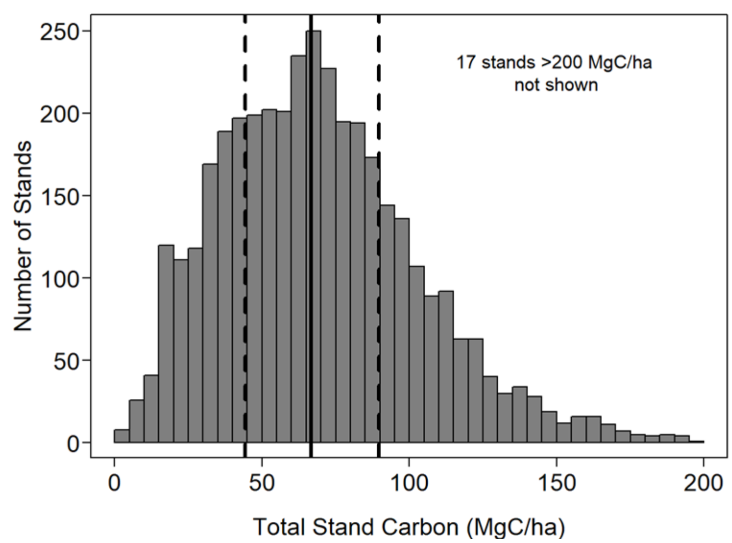
The methods presented in this section offer a means to quantify an important but limited part of avoided wildfire emissions. They are a starting point for land managers seeking to understand the immediate impacts of low-severity prescribed burns and compare them to GHG impacts from higher severity fire events. They are not sufficient as a way to quantify avoided wildfire emissions from forest management activities such as fuel treatments. Such efforts would require more detailed accounting of the carbon costs of the forest management activity (including prescribed fire, diesel and gasoline for transportation and other needs to complete the project), a probabilistic accounting for future fire likelihood and intensity, modeling of regeneration and forest growth over time, spatial information on how the fuel treatment changes probability of burning and intensity on adjacent land, and a long-term model of the fate of burned carbon stocks, regeneration potential, and subsequent disturbance potential.

Uncertainty

FIA Data

The FFE-FVS simulations are based on FIADB TREE table and DDW table data, so uncertainties and errors of these data will be propagated into simulation results. The FIADB DDW table provides estimates of surface fuel loading, litter, duff, and woody material, based on sampling at eight locations for litter and duff and transects for woody material. Perhaps the greatest source of uncertainty in current inventories of standing carbon on the landscape is extrapolation from FIA plots to the rest of the landscape (McGlynn et al., 2019). Surface fuel loading can have tremendous spatial variability (Keane et al., 2012a, 2012b), and the size of a single FIA plot may be inadequate to capture variability in fuel loading across the landscape. Additionally, the diversity in species composition and proportion of consumed biomass can be highly variable. The stochastic nature of fire intensity and severity and the variability of fuels across the landscape compound this uncertainty.

Theoretically, the simulation of multiple FIA plots per forest type captures some of this inherent variability (e.g., see figure 5-8), but when the median simulation estimates are used in reporting, they cannot convey variability in fire effects (see Binning section below). This section addresses this by including 25th and 75th percentiles for each bin as well.



The solid vertical line marks the median value ("best estimate") and the dashed vertical lines mark 25th and 75th percentiles.

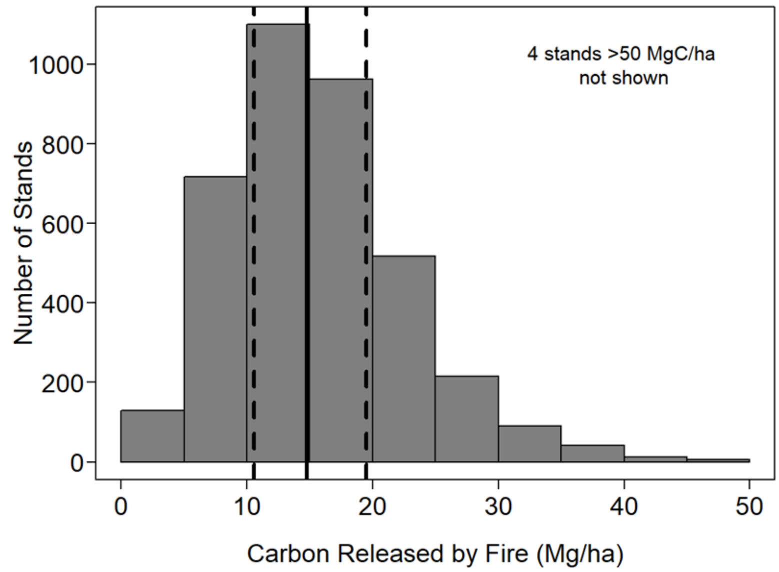
Figure 5-8. Distribution of Total Stand Carbon Prefire in 3,799 Rocky Mountain South Region Ponderosa Pine Forest Stands (Forest Type Group Code = 220)

Fuel Consumption

The FFE-FVS simulations were run using a matrix of fire-related parameters (wind speed, fuel moisture, temperature, and burn patchiness) to approximate the target mortality levels of the fire severity scenarios listed in table 5-12. Consumption of surface fuels, herbs, and shrubs was simulated by FFE-FVS (Rebain, 2010; Reinhardt and Crookston, 2003). Consumption of DDW, litter and duff are largely driven by fuel moisture, although several region-/cover-type-specific algorithms are used for duff.

Binning

The carbon pool and GHG emission estimates are coarsely stratified based on region and forest type, with significant variability among fuel strata. This could result in the binned estimates deviating significantly from true values at any given forest stand. For example, figure 5-9 shows the distribution of simulated total carbon released by moderate-severity wildfire in 3,799 Ponderosa pine forest stands in the Rocky Mountain South region. The total carbon release for half of the stands falls within ±4.5 metric tons carbon per hectare (Mg C/ha) of the best estimate value of 14.8 Mg C/ha. However, one in four stands differs from the best estimate by more than 50 percent (< 7.3 Mg C/ha or > 22.1 Mg C/ha). The span of estimates is likely largely driven by variation in the percent live tree cover and loading of litter, duff, and DDW on different FIA plots within the same region and forest type. Total stand carbon prefire for the same Rocky Mountain South Region Ponderosa pine forest simulations is shown in figure 5-8. Prefire, half of the stands fall within ±22.7 Mg C/ha of the best estimate value of 66.8 Mg C/ha for total stand carbon. Thus, due to the high natural variability of stand structure and carbon pool loading across the sites aggregated by region and forest type in the binning, the median values reported as best estimates may not correspond well with what is on small landholdings.



The solid vertical line marks the median value ("best estimate") and the dashed vertical lines mark 25th and 75th percentiles.

Figure 5-9. Distribution of Total Carbon Released by a Moderate-Severity Wildfire in 3,799 Rocky Mountain South Region Ponderosa Pine Forest Stands (Forest Type Code = 220).

5.2.4 Urban Forest Management

Method for Estimating GHG Flux From Urban Forest Management

- The i-Tree tools currently provide the most comprehensive way to estimate flux from urban forest management. The available tools have varying levels of complexity, thus lending themselves to various user backgrounds.

5.2.4.1 Description of Method

There are three general methods for estimating carbon storage and annual sequestration in urban forests:

- Gathering data on the ground from trees in the field. This method will produce the most accurate estimates, but with increased costs and time spent by the landowner.

- Collecting photointerpretation of tree canopy from aerial imagery. This approach requires a minor time commitment and an ability to discern various geographic features in the imagery. Its accuracy is limited (see table 5-13) due to the conversion from canopy area to carbon data without detailed information on the trees being analyzed.
- Using preexisting and summarized carbon data of specific geographies from an online geospatial database. This approach quickly provides free basic data for the geography of interest but may be out of date or not have a fine enough resolution to be accurate at the local scale.

i-Tree (see box 5-10 for background) is a suite of free software tools designed to assess and value the urban forest resource, understand forest risk, and develop sustainable forest management plans to improve environmental quality and human health. i-Tree tools and resources are referenced for the field data collection method, aerial data collection method, and online spatial database method. Note that these methods may be used in rural areas as well as in urban areas of the United States.

Box 5-10. The i-Tree Suite

i-Tree is a dynamic system of tree benefit estimation science built on a collaborative platform facilitated by a public-private partnership between the Davey Tree Expert Company and the USDA, Forest Service. i-Tree tools calculate not only carbon values, but also many other tree benefits that help inform urban and community forest management. i-Tree serves a growing domestic and global community of users and contributors with online and downloadable tools, user support, and a website with substantial informational and training resources. Collaborators continue to update and expand i-Tree with new tools, science, and reporting options. Because i-Tree is always updating, users are encouraged to visit the i-Tree website at www.itreetools.org for the most up-to-date tools (including the ones listed in this section) and resources including manuals, tutorials, trainings, example projects, and guidance. Some specific i-Tree tools are described in appendix 5-A.6.

The section outlines the use of i-Tree tools to estimate carbon storage and annual sequestration and additional carbon effects, as well as many other environmental services. It offers Level 1, Level 2, and Level 3 approaches that correspond to specific levels of complexity and precision (as described in section 5.1.6).

Table 5-13 compares each of the i-Tree programs. i-Tree programs automatically generate output values of carbon storage and annual sequestration as well as other environmental service values. See section 5-A.1.1 for a description of different approaches to use to collect activity data.

Table 5-13. Data Gathering Methods and Corresponding i-Tree Tools

	Field Data Method	Aerial Data Method	Online Geospatial Database Method
Program	i-Tree MyTree[a] i-Tree Eco[b] i-Tree Design[c]	i-Tree Canopy[d]	i-Tree Landscape[e]
Time needed	Time commitment to take field measurements	Less time to extract aerial data from an existing database	No time, since all data come from existing landcover data

	Field Data Method	Aerial Data Method	Online Geospatial Database Method
Access needed to gather data	Requires access to one or more sample locations across an area	Does not require field measurements, only a computer with internet access	Does not require field measurements, only a computer with internet access
Precision/ accuracy	Increases specificity (relative to the other methods) and accuracy	Returns a more approximate estimate	Returns a more approximate estimate depending on data resolution in the area of interest
Available outputs	Provides a variety of output data including current carbon stock, annual carbon sequestration, and long-term effects	Provides only information on total carbon stored and annual carbon sequestration	Provides only information on total carbon stored and annual carbon sequestration

[a] https://mytree.itreetools.org/

[b] https://www.itreetools.org/tools/i-tree-eco

[c] https://design.itreetools.org/

[d] https://canopy.itreetools.org/

[e] https://landscape.itreetools.org/

i-Tree MyTree is an online program designed for cellphone use that directs users to enter a location and take simple field measurements of tree species, condition, diameter or circumference, and sun exposure to obtain carbon storage and annual sequestration, altered building energy use, and several other environmental service values. Output values are provided in a nutrition label format that can be used in Level 2 calculations. More intensive and precise field data collection methods, using i-Tree Eco, are outlined under Level 3.

i-Tree Design is an online tool for estimating individual tree benefits of carbon dioxide, air pollution, stormwater impacts and energy savings. Users plot an existing tree or planting location on a map, select species, enter trunk diameter or circumference, and select the general condition of the tree to obtain the estimated tree benefits. i-Tree Design estimates tree benefits for the current year and up to 99 years in the future. Total benefits to date based on estimated tree age are also provided. Multiple trees and buildings can be modeled.

i-Tree Canopy is an online photointerpretation tool with underlying Google Earth imagery. Using this tool and online directions, one establishes the location of analysis, enters information about that location, and delineates the area of interest (by drawing a polygon around it or providing a shapefile). With the area of analysis established, i-Tree Canopy automatically generates random sample points, which the interpreter uses to assess tree canopy and/or other land cover values. From the point interpretation and other user inputs, i-Tree Canopy calculates the area covered by tree canopy values and uses the location-specific i-Tree data and models to calculate carbon storage and annual sequestration as well as several other environmental service benefits. The user follows the online instructions to complete the analysis and can export report(s). The i-Tree Canopy values can be exported and used for Level 2 calculations. See appendix 5-A.1.1 for instructions on how to use i-Tree Canopy.

i-Tree Landscape is an online interactive geodatabase that hosts summarized values of carbon storage and annual sequestration as well as many other pieces of forest, environmental, and census information. Using Landscape and following its online directions, one begins by identifying the geographic region to analyze. The smallest level of analyzed geography available in Landscape is the census block group level, but larger census and several other types of geographies are available (i.e., census tracts, watersheds, counties, national forests). Carbon estimates of storage and annual sequestration are calculated from tree cover estimates, themselves derived from land cover data ranging from submeter to 30-meter resolution depending on the area of interest. However, the 30-meter resolution estimates of tree cover, which are most common across the United States, tend to underestimate tree cover (Nowak and Greenfield, 2010) and thus tend to underestimate carbon effects. In addition to carbon, i-Tree Landscape provides additional information of interest for the geography selected. Data from the area of interest can be exported in report(s) and can be used for Level 2 calculations.

MyTree, Canopy, and Landscape can all be used to measure carbon effects over time:

- i-Tree MyTree provides carbon estimates forecasted for a 20-year period and can also be used later to remeasure the trees originally surveyed.
- i-Tree Canopy instructions outline a process to recheck established photointerpretation points with newer imagery (and can check past values if imagery is available).
- i-Tree Landscape has values for different points in time to compare.

Level 1 Approach

To get basic carbon values including storage and annual sequestration, the easiest and most accessible options are to use i-Tree, MyTree, or iTree Design for field data collection, i-Tree Canopy for aerial data collection, or i-Tree Landscape for the online geospatial database method.

Level 2 Approach

Level 2 uses other tools, outputs from Level 1 analyses, and the lookup table values included in this chapter to get a fuller accounting of additional carbon effects and track those impacts over time. MyTree, i-Tree Canopy, and i-Tree Landscape outputs can be used with the lookup tables to account for carbon effects beyond simple storage and annual sequestration. In addition, many i-Tree tools generate some of the additional carbon effects as well as many other environmental service values so that additional work may not be needed.

Use the i-Tree Harvest Carbon Calculator (originally known as the PRESTO Wood Calculator) to estimate the amount of carbon stored in HWPs (i-Tree, 2022b) per forest area (100-year average and total remaining after 100 years or total remaining each first 10 decades as metric tons C/ha with the following categories: products, landfills, stored HWP (sum of products and landfills), emissions with energy capture, and emissions without energy capture). Carbon estimates are based on estimated harvest volumes derived from geographic region, stand size, hardwood or softwood wood type proportions, and sawlog and pulpwood proportions within wood types. This tool offers the means to include HWPs in carbon accounting and carbon credits and to explore the carbon impacts of changing the proportions of longer- and shorter-lived wood products for a given forest stand. It is similar to the Level 1 approach described in the HWP section (section 5.2.2), but it:

- Does not allow the user to choose a forest type.
- Does not allow the user to enter harvest volumes or weights directly.
- Does not include fuelwood or bark.
- Does not include percent loss (immediate disposition) at installation of solid wood products (~8 percent).

- Does not offer both exponential and chi square curves for product in use lifespans.
- Does not use the most recent EPA WARM disposition ratios (recycling, landfills, emitted with and without energy capture).
- Does not report emissions in CO_2-eq.
- Does not connect to a substitution benefit calculator.

For estimating emission effects associated with maintaining urban forests, the following steps are suggested:

1. Determine vehicle use related to tree maintenance. Determine the number of miles driven by various vehicle types.
2. Calculate carbon emissions from vehicles. To estimate carbon emissions from vehicles, the latest fuel efficiency information (in miles per gallon) will be needed for each vehicle class. Divide the miles driven by the vehicle class miles per gallon to determine the total gallons of gasoline (or other fuel) used. Multiply total gallons (or other units) used by the emission factor in table 5-14 to estimate carbon emissions from vehicle use (Nowak et al., 2002).
3. Determine maintenance equipment use. Estimate the number of run hours for all fossil-fuel-based maintenance equipment used on trees (e.g., chain saws, chippers, aerial lifts, backhoes, stump grinders). Estimates of run time for various pruning and removal equipment are given in table 5-15.
4. Calculate carbon emissions from maintenance equipment using equation 5-8. Typical load factors and average carbon emissions for equipment are given in table 5-16.
5. Calculate total maintenance carbon emissions by summing carbon emissions from all vehicles and maintenance equipment.

To determine current net annual urban forest effect on carbon, subtract the carbon emissions from tree maintenance from net carbon sequestration from trees, then add net altered carbon emissions from altered building energy use effects.

Equation 5-8: Calculating Carbon Emissions From Maintenance Equipment

$$C = N \times HRS \times HP \times LF \times E$$

Where:

C	=	carbon emissions (g)
N	=	number of units (dimensionless)
HRS	=	hours used
HP	=	average rated horsepower
LF	=	typical load factor (dimensionless), provided in table 5-16
E	=	average carbon emissions per unit of use (g/hp/hour) (U.S. EPA, 1991)

To determine how tree and maintenance effects on carbon change through time, all the photointerpretation points and the field plots or trees inventoried can be remeasured; subtract previous years' results from most recent years' results to estimate changes in carbon stock, then divide by the number of elapsed years to determine net annual carbon effects, including altered building energy use effects. In addition, maintenance activity estimates should be updated when the remeasurement occurs.

Level 3 Approach

The Level 3 approach uses i-Tree Eco, which is based on field data from samples and inventories, in addition to user input. For further carbon accounting beyond the outputs of i-Tree Eco, calculations from Level 2 can be used.

i-Tree Eco is a downloadable desktop application that uses data collected from trees to assess forest structure, health, threats, and ecosystem services and values for a tree population. It calculates tree benefits including total carbon storage and net annual carbon sequestration, as well as additional benefits such as energy savings, pollution removal, and hydrologic benefits. Carbon storage and sequestration are calculated for each individual tree using species-specific allometric equations (Nowak, 2021). In addition to species, inputs of tree size, condition, and crown light exposure must be gathered to produce carbon storage and sequestration values.

i-Tree Eco also calculates building energy use effects, which it converts to carbon emission factors based on State average energy distribution. Energy effects estimates are based on sampling proximity of trees near buildings within various tree size, distance, and direction classes from a building.

5.2.4.2 Activity Data

Depending on the method used and output values desired, additional steps, data inputs, and/or calculations may be needed to help account for carbon effects beyond the basic values of carbon storage and annual sequestration.

Table 5-14. Emission Factors for Common Transportation Fuels

Fuel	Emissions (Pounds CO_2 per Unit Volume)
B20 biodiesel	17.71 per gallon
B10 biodiesel	19.93 per gallon
Diesel fuel (no.1 and no. 2)	22.15 per gallon
E85 ethanol	2.9 per gallon
E10 ethanol	17.41 per gallon
Gasoline	19.36 per gallon
Natural gas	119.90 per 1,000 cubic feet
Propane	5.74 per gallon

Source: U.S. DOE (2007), table 1.D.1.

Table 5-15. Total Hours of Equipment Run Time by dbh Class for Tree Pruning and Removal

	Pruning				Removal					
dbh	2.3 hp Saw	3.7 hp Saw	Bucket Truck[a]	Chipper[b]	2.3 hp Saw	3.7 hp Saw	7.5 hp Saw	Bucket Truck[a]	Chipper[b]	Stump Grinder[b]
1–6	0.05	NA	NA	0.05	0.3	NA	NA	0.2	0.1	0.25
7–12	0.1	NA	0.2	0.1	0.3	0.2	NA	0.4	0.25	0.33
13–18	0.2	NA	0.5	0.2	0.5	0.5	0.1	0.75	0.4	0.5
19–24	0.5	NA	1.0	0.3	1.5	1.0	0.5	2.2	0.75	0.7
25–30	1.0	NA	2.0	0.35	1.8	1.5	0.8	3.0	1.0	1.0

dbh	Pruning				Removal					
	2.3 hp Saw	3.7 hp Saw	Bucket Truck[a]	Chipper[b]	2.3 hp Saw	3.7 hp Saw	7.5 hp Saw	Bucket Truck[a]	Chipper[b]	Stump Grinder[b]
31–36	1.5	0.2	3.0	0.4	2.2	1.8	1.0	5.5	2.0	1.5
36+	1.5	0.2	4.0	0.4	2.2	2.3	1.5	7.5	2.5	2.0

This table is based on ACRT data (D. Wade and P. Dubish, personal communication, 1995, as cited in Nowak et al., 2002). It assumes that crews work efficiently and equipment is not run idle (Nowak et al., 2002).

a Mean hp = 43 (U.S. EPA, 1991)

b Mean hp = 99 (U.S. EPA, 1991)

Table 5-16. Typical Load Factors, Average Carbon Emissions, and Total Carbon Emissions for Various Maintenance Equipment

Equipment	Typical Load Factor[a]	Average Carbon Emission (g/hp/Hour)[b]	Total Carbon Emission (kg/Hour)[c]
Aerial lift	0.505	147.2	3.2[d]
Backhoe	0.465	147.3	5.3[e]
Chain saw <4 hp	0.500	1,264.4	1.5[f]
Chain saw >4 hp	0.500	847.5	3.2[g]
Chipper/stump grinder	0.370	146.4	5.4[h]

Sources: U.S. EPA, 1991 (load factors); Nowak et al., 2002 (average carbon emissions, total carbon emissions).

a Average value from two studies (a conservative load factor of 0.5 from inventory B was used for chain saws over 4 hp due to disparate inventory estimates; inventory average for this chain saw type was 0.71).

b Calculated from estimates of carbon monoxide (U.S. EPA, 1991), hydrocarbon crankcase and exhaust (U.S. EPA, 1991), and CO_2 emissions (W. Charmley, personal communication, 1995, as cited in Nowak et al., 2002), adjusted for in-use effects. Total carbon emissions were calculated based on the proportion of carbon of the total atomic weight of the chemical emission. Multiply by 0.0022 to convert to pounds/hp/hour.

c Multiply by 2.2 to convert to pounds/hour.

d Mean hp = 43 (U.S. EPA, 1991).

e Mean hp = 77 (U.S. EPA, 1991).

f hp = 2.3

g hp = 7.5

h Mean hp = 99 (U.S. EPA, 1991).

5.2.4.3 Limitations and Uncertainty

All three Level approaches can provide carbon estimates for urban areas, with differing degrees of uncertainty and level of effort required. All approaches can also be improved with more field data collection in urban areas, and with model and method improvements related to carbon estimation.

Estimates based on urban tree data collection have fewer limitations than estimates based on aerial data collection, but some limitations exist (Nowak et al., 2008). The main advantage of carbon estimation using the tree measurement approach and i-Tree is having accurate estimates of the tree population (e.g., species, size, distribution) with a calculated level of precision. The modeled carbon values are estimates based on forest-derived allometric equations (Nowak, 1994, 2021; Nowak and Crane, 2002; Nowak et al., 2013). The carbon estimates yield a standard error of the estimate based on sampling error, rather than error of estimation.

Estimation error is unknown, and likely larger than the reported sampling error. Estimation error includes the uncertainty of using biomass equations and conversion factors, which may be large, as well as measurement error, which is typically small. The standardized carbon values (e.g., kg C/ha or pounds C/acre of tree cover) fall in line with values for forests (Birdsey and Heath, 1995), but values for cities (places) can be higher, likely due to a larger proportion of large trees in city environments and relatively fast growth rates due to a more open urban forest structure (Nowak and Crane, 2002; Nowak et al., 2013).

There are various means to help improve the carbon storage and sequestration estimates for urban trees. Carbon estimates for open-grown urban trees are adjusted downward based on field measurements of trees in the Chicago area (Nowak, 1994). This adjustment may lead to conservative estimates of carbon. More research is needed on the applicability of forest-derived equations to urban trees. In addition, more urban tree growth data are needed to better understand regional variability of urban tree growth under differing site conditions (e.g., tree competition) for better annual sequestration estimates. Average regional growth estimates are used based on limited measured urban tree growth data standardized to length of growing season and crown competition.

Estimates of maintenance emissions and altered building energy use effects are also rather coarse. Accurate maintenance emission estimates require good estimates of vehicle and maintenance equipment use; then they rely on an average multiplier for emissions from the literature. Energy effects estimates are based on sampling proximity of trees near buildings within various tree size, distance, and direction classes from a building. Energy factors, converted to carbon emission factors based on State average energy distribution (e.g., electricity, oil), are applied to trees in each building location class based on U.S. climate zone and average building types in a State to estimate energy effects (see McPherson and Simpson, 1999). Though these estimates are coarse, with an unknown certainty, they are based on reasonable approaches that provide defensible estimates of effects. Note that emission reductions from altered building energy use effects might also be implicitly included in any emission estimation an entity might perform based on actual energy use data (e.g., meter readings) for the building in question.

Estimates based on aerial tree canopy effects have the same limitations as field data approaches, plus some additional limitations and advantages. The advantages include a simple, quick, and accurate means to assess the amount of canopy cover in an area, with measures that are repeatable through time. The disadvantage is that the application uses a lookup value from a table (e.g., mean value per unit of canopy cover) to estimate carbon effects. Though the tree cover estimate will be accurate with known uncertainty (i.e., standard error), the carbon multipliers may be off depending on the urban forest characteristics. If average multipliers are used, the accuracy of those estimates will decline as the difference increases between the local urban characteristics and the values of the average multipliers. If local field data are not collected, then the discrepancy between the urban forest's characteristics and those of average values is unknown. However, local estimates may be inaccurate depending on the extent to which characteristics of the local urban forest diverge from the average values.

Estimates based on the landscape tree canopy effects have the same limitations as field data and aerial approaches, plus some additional limitations and advantages. This method is the simplest in that it only requires the user to select an area of interest for analysis. When high-resolution (sub-meter pixel) canopy cover data are available, estimates may be more accurate than those produced by the aerial method. However, where only coarse cover data are available, carbon analysis will be less accurate due to imprecise estimations of canopy cover. Additionally, boundary selection is limited by the tool, such that the smallest urban analysis unit is the census block group.

5.3 Chapter 5 References

Ager, A.A., M.A. Finney, A. McMahan, J. Cathcart. 2010. Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. *Natural Hazards and Earth Systems Science*, 10: 2515–2526. https://doi.org/10.5194/nhess-10-2515-2010.

Aguilera, R., T. Corringham, A. Gershunov, T. Benmarhnia. 2021. Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications*, 12: 1493. https://doi.org/10.1038/s41467-021-21708-0.

Alanya-Rosenbaum, S., and R.D. Bergman. 2020. *Cradle-to-grave life-cycle assessment of wooden pallet production in the United States*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/treesearch/pubs/61866.

Albaugh, T.J., E.D. Vance, C. Gaudreault, T.R. Fox, H.L. Allen, J.L. Stape, R.A. Rubilar. 2012. Carbon emissions and sequestration from fertilization of pine in the southeastern United States. *Forest Science*, 58(5): 419–429. https://doi.org/10.5849/forsci.11-050.

Alerich, C.L., L. Klevgard, C. Liff, P.D. Miles, B. Knight. 2005. *The forest inventory and analysis database: Database description and users guide version 2.0*. U.S. Department of Agriculture, Forest Service.

Alvarado, M.J., K.C. Barsanti, S.H. Chung, D.A. Jaffe, C.T. Moore. 2022. Chapter 6: Smoke chemistry. In Peterson, D.L., S.M. McCaffrey, T. Patel-Weynand (eds.). *Wildland fire smoke in the United States: A scientific assessment.* Springer. https://www.fs.usda.gov/research/publications/book/wildfiresmoke/wildfiresmokefull.pdf.

Anderson, N., J. Young, K. Stockmann, K. Skog, S. Healey, D. Loeffler, J.G. Jones, et al. 2013. *Regional and forest-level estimates of carbon stored in harvested wood products from the United States Forest Service Northern Region, 1906–2010*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/RMRS-GTR-311.

ASCC. 2022. *Adaptive Silviculture for Climate Change: About.* Adaptive Silviculture for Climate Change. https://www.adaptivesilviculture.org/.

Basiliko, M., A. Khan, C.E. Prescott, R. Roy, S.J. Grayston. 2009. Soil greenhouse gas and nutrient dynamics in fertilized western Canadian plantation forests. *Canadian Journal of Forest Research,* 39(6): 1220–1235. https://doi.org/10.1139/X09-043.

Bates, L., B. Jones, E. Marland, G. Marland, T. Ruseva, T. Kowalczyk, J. Hoyle. 2017. Accounting for harvested wood products in a forest offset program: Lessons from California. *Journal of Forest Economics,* 27: 50–59.

Bechtold, W.A., and P.L. Patterson. 2005. *The enhanced forest inventory and analysis program—national sampling design and estimation procedures*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/SRS-GTR-80.

Bergman, R., M. Puettmann, A. Taylor, K.E. Skog. 2014. The carbon impacts of wood products. *Forest Products Journal*, 64(7-8): 220–231. https://doi.org/10.13073/FPJ-D-14-00047.

Birdsey, R.A. 1996. Carbon storage for major forest types and regions in the conterminous United States. In Sampson, N., and D. Hair. *Forests and global change, volume 2.* American Forests.

Birdsey, R.A., and L.S. Heath. 1995. *Carbon changes in U.S. forests*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.5962/bhl.title.99533.

Birdsey, R.A., K. Pregitzer, A. Lucier. 2006. Forest carbon management in the United States: 1600–2100. *Journal of Environmental Quality,* 35: 1461–1469.

Brandt, J.P., T.A. Morgan, T. Dillon, G.J. Lettman, C.E. Keegan, D.L. Azuma. 2006. *Oregon's forest products industry and timber harvest, 2003*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/PNW-GTR-681.

Bright, R.M., E. Davin, T. O'Halloran, J. Pongratz, K. Zhao, A. Cescatti. 2017. Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change,* 7: 296–304. https://doi.org/10.1038/nclimate3250.

Brown, S., B. Lim, B. Schlamadinger. 1998. *Evaluating approaches for estimating net emissions of carbon dioxide from forest harvesting and wood products.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/dakar.pdf.

Burrill, E.A., A.M. Wilson, J.A. Turner, S.A. Pugh, J. Menlove, G. Christiansen, B.L. Conkling, et al. 2018. *The Forest Inventory and Analysis database: Database description and user guide version 8.0 for phase 2.* U.S. Department of Agriculture, Forest Service. https://www.fia.fs.usda.gov/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf.

Burrill, E.A., A.M. DiTommaso, J.A. Turner, S.A. Pugh, J. Menlove, G. Christiansen, C.J. Perry, et al. 2021. *The Forest Inventory and Analysis database: Database description and user guide version 9.0.1 for phase 2.* U.S. Department of Agriculture, Forest Service. https://www.fia.fs.usda.gov/library/database-documentation/current/ver90/FIADB%20User%20Guide%20P2_9-0-1_final.pdf.

Cai, H., X. Wang, J.H. Kim, A. Gowda, M. Wang, J. Mlade, S. Farbman, et al. 2022. Whole-building life-cycle analysis with a new GREET® tool: Embodied greenhouse gas emissions and payback period of a LEED-Certified library. *Building and Environment*, 209: 108664. https://doi.org/10.1016/j.buildenv.2021.108664.

Campbell, J.L., M.E. Harmon, S.R. Mitchell. 2012. Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? *Frontiers in Ecology and the Environment*, 10(2): 83–90. https://doi.org/10.1890/110057.

Cao, J., J.F. Adamowski, R.C. Deo, X. Xu, Y. Gong, Q. Feng. 2019. Grassland degradation on the Qinghai-Tibetan Plateau: Reevaluation of causative factors. *Rangeland Ecology & Management*, 72(6): 988–995. https://doi.org/10.1016/j.rama.2019.06.001.

CARB. 2015. *Compliance offset protocol: U.S. forest projects, Appendix C*. California Environmental Protection Agency, Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/cap-and-trade/protocols/usforest/forestprotocol2015.pdf.

Chojnacky, D.C., L.S. Heath, J.C. Jenkins. 2014. Updated generalized biomass equations for North American tree species. *Forestry*, 87: 129–151. https://doi.org/10.1093/forestry/cpt053.

Christensen, G.A., A.N. Gray, O. Kuegler, N.A. Tase, M. Rosenberg. 2021*. AB 1504 California forest ecosystem and harvested wood product carbon inventory: 2019 reporting period data update*. California Department of Forestry and Fire Protection and California Board of Forestry and Fire Protection. https://bof.fire.ca.gov/media/beddx5bp/6-final_forest_ecosys_hwp_c_2019_feb2021_all_ada.pdf.

Cordero, P.R.F., K. Bayly, P.M. Leung, C. Huang, Z. Islam, R.B. Schittenhelm, G.M. King, et al. 2019. Atmospheric carbon monoxide oxidation is a widespread mechanism supporting microbial survival. *The ISME Journal*, 13: 2868–2881. https://doi.org/10.1038/s41396-019-0479-8.

Crookston, N.L., and G.E. Dixon. 2005. The Forest Vegetation Simulator: A review of its structure, content, and applications. *Computers and Electronics in Agriculture*, 49(1): 60–80. https://doi.org/10.1016/j.compag.2005.02.003.

CSF. 2022. Climate-smart forestry.org: Amplifying the climate benefits of the forestry sector. https://www.climatesmartforestry.org/.

Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, et al. 2019. Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, 116(13): 6193–6198. https://doi.org/10.1073/pnas.1815107116.

de Silva Alves, J.W., P. Boeckx, K. Brown, R. Hoppaus, C. Jubb, T. Kerr, T. Kleffelgaard, et al. 2000. Chapter 5: Waste. In Penman, J., D. Kruger, I. Galbally, T. Hiraishi, B. Nyenzi, S. Emmanuel, L. Buenida, et al. (eds.). *Good practice guidance and uncertainty management in national greenhouse gas inventories*. Institute for Global Environmental Strategies for the Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Di Gregorio, A., and L.J.M. Jansen. 2005. *Land Cover Classification System: Classification concepts and user manual.* Environment and Natural Resource Series 8. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/y7220e/y7220e00.htm.

Dixon, G.E. 2002 (rev. 2022). *Essential FVS: A user's guide to the Forest Vegetation Simulator*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/fmsc/ftp/fvs/docs/gtr/EssentialFVS.pdf.

Domke, Grant M.; Walters, Brian F.; Giebink, Courtney L.; Greenfield, Eric J.; Smith, James E.; Nichols, Michael C.; Knott, Jon A.; Ogle, Stephen M.; Coulston, John W.; Steller, John. 2023. Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990-2021. Resour. Bull. WO-101. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 10 p. https://doi.org/10.2737/WO-RB-101.

Domke, G.M., C.W. Woodall, J.E. Smith. 2011 Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management,* 6: 14. https://doi.org/10.1186/1750-0680-6-14.

Domke, G.M., C.H. Perry, B.F. Walters, C.W. Woodall, M.B. Russell, J.E. Smith. 2016. Estimating litter carbon stocks on forest land in the United States. *Science of the Total Environment*, 557–558: 469–478. https://doi.org/10.1016/j.scitotenv.2016.03.090.

Domke, G.M., C.H. Perry, B.F. Walters, L.E. Nave, C.W. Woodall, C.W. Swanston. 2017. Toward inventory-based estimates of soil organic carbon in forests of the United States. *Ecological Applications*, 27(4): 1223–1235. https://doi.org/10.1002/eap.1516.

Domke, G.M., S.N. Oswalt, B.F. Walters, R.S. Morin. 2020. Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the National Academy of Sciences*, 117(40): 24649–24651. https://doi.org/10.1073/pnas.2010840117.

Domke, G.M., B.F. Walters, D.J. Nowak, J.E. Smith, M.C. Nichols, S.M. Ogle, J.W. Coulston, et al. 2021. *Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990–2019*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/FS-RU-307.

Doraisami, M., R. Kish, N.J. Paroshy, G.M. Domke, S.C. Thomas, A.R. Martin. 2022. A global database of woody tissue carbon concentrations. *Scientific Data,* 9: 284. https://doi.org/10.1038/s41597-022-01396-1.

Finney, M.A., R.C. Seli, P.L. Andrews. 2003. Modeling post-frontal combustion in the FARSITE fire area simulator. In *Proceedings of the Second International Wildland Fire Ecology and Fire Management Congress, Orlando, FL.*

Forest Products Laboratory. 2010. *Wood handbook: Wood as an engineering material*. U.S. Department of Agriculture, Forest Service. https://www.fpl.fs.usda.gov/documnts/fplgtr/fpl_gtr190.pdf.

Forest Products Laboratory. 2021. *Wood handbook: Wood as an engineering material*. U.S. Department of Agriculture, Forest Service. https://www.fpl.fs.usda.gov/documnts/fplgtr/fplgtr282/front_matter_fpl_gtr282.pdf.

Freed, R., and C. Mintz. 2003 (August 29). *Revised input data for WOODCARB.* Letter to H. Ferland (EPA), K. Skog (USDA), T. Wirth (EPA), and E. Scheehle (EPA). On file with Forest Products Laboratory, Madison, WI.

Fuzzi, S., U. Baltensperger, K. Carslaw, S. Decesari, H. Denier van der Gon, M.C. Facchini, D. Fowler, et al. 2015. Particulate matter, air quality and climate: lessons learned and future needs. *Atmospheric Chemistry and Physics*. 15: 8217–8299. https://doi.org/10.5194/acp-15-8217-2015.

Ganguly, I., F. Pierobon, T.C. Bowers, M. Huisenga, G. Johnston, I.L. Eastin. 2018. "Woods-to-wake" life cycle assessment of residual woody biomass based jet-fuel using mild bisulfite pretreatment. *Biomass and Bioenergy*, 108: 207–216. https://doi.org/10.1016/j.biombioe.2017.10.041.

Ganguly, I., F. Pierobon, E. Sonne Hall. 2020. Global warming mitigating role of wood products from Washington state's private forests. *Forests,* 11(2): 194. https://doi.org/10.3390/f11020194.

Goslee, K., S.M. Walker, A. Grais, L. Murray, F. Casarim, S. Brown. 2016. Module C-CS: Calculations for estimating carbon stocks. In *LEAF technical guidance series for the development of a forest carbon monitoring system for REDD+.* https://winrock.org/wp-content/uploads/2018/08/Winrock-Guidance-on-calculating-carbon-stocks.pdf

Gustavsson, L., and R. Sathre. 2011. Energy and CO_2 analysis of wood substitution in construction. *Climate Change,* 105: 129–153. https://doi.org/10.1007/s10584-010-9876-8.

Hardy, C.C. 1998. *Guidelines for estimating volume, biomass and smoke production for piled slash*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/treesearch/pubs/26244.

Harmon M.E. 2019. Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions. *Environmental Research Letters,* 14(6): 065008. https://doi.org/10.1088/1748-9326/ab1e95.

Harmon, M.E., B. Fasth, C.W. Woodall, J. Sexton. 2013. Carbon concentration of standing and downed woody detritus: Effects of tree taxa, decay class, position, and tissue type. *Forest Ecology and Management,* 291: 259–267.

Heisler, G.M. 1986. Effects of individual trees on the tolar radiation climate of small buildings. *Urban Ecology,* 9: 337–359. https://www.nrs.fs.usda.gov/pubs/jrnl/1986/nrs_1986_heisler_001.pdf.

Hoover, C.M. 2008. Field measurements for forest carbon monitoring: A landscape-scale approach. Springer.

Hoover, C.M., and S.A. Rebain. 2011. *Forest carbon estimation using the Forest Vegetation Simulator: Seven things you need to know*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/treesearch/pubs/37449.

Hoover, C.M., and J.E. Smith. 2021. Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States. *Carbon Balance and Management,* 16(1): 574. https://doi.org/10.1186/s13021-021-00179-2.

Hoover, C., R. Birdsey, B. Goines, P. Lahm, Y. Fan, D. Nowak, S. Prisley, et al. 2014. Chapter 6: Quantifying greenhouse gas sources and sinks in managed forest systems. In Eve, M., D. Pape, M. Flugge, R. Steele, D. Man, M. Riley-Gilbert, S. Biggar. *Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory*. Technical Bulletin 1939. U.S. Department of Agriculture.

Hoover, C.M., E. Smith-Mateja, N. Balloffet. 2023. *Estimates of forest ecosystem carbon for common reforestation scenarios in the United States.* Gen. Tech. Rep. NRS-209. U.S. Department of Agriculture. https://doi.org/10.2737/NRS-GTR-209.

Hubbard, S.S., R.D. Bergman, K. Sahoo, S. Bowe. 2020. *CORRIM report: A life cycle assessment of hardwood lumber production in the northeast and north central United States*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/treesearch/pubs/60571.

Hurmekoski, E., C.E. Smyth, T. Stern, P.J. Verkerk, R. Asada. 2021. Substitution impacts of wood use at the market level: A systematic review. *Environmental Research Letters*, 16(12): 123004. https://doi.org/10.1088/1748-9326/ac386f.

Hurteau, M.D., S. Liang, K.L. Martin, M.P. North, G.W. Koch, B.A. Hungate. 2016. Restoring forest structure and process stabilizes forest carbon in wildfire-prone southwestern ponderosa pine forests. *Ecological Applications*, 26(2): 382–391. https://doi.org/10.1890/15-0337.

Ingerson, A. 2011. Carbon storage potential of harvested wood: summary and policy implications. *Mitigation and Adaptation Strategies for Global Change,* 16: 307–323. https://doi.org/10.1007/s11027-010-9267-5.

IPCC. 2003. *Good practice guidance for land use, land-use change and forestry*. Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_FULL.pdf.

IPCC. 2006. *2006 IPCC guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

IPCC. 2007. *Climate change 2007: The physical science basis. Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental

Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf.

IPCC. 2013. *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf.

IPCC. 2018. *Annex I: Glossary* [Matthews, J.B.R. (ed.)]. In: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press. https://doi.org/10.1017/9781009157940.008.

IPCC. 2019. *Glossary*. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2019/06/19R_V0_02_Glossary_advance.pdf.

i-Tree. 2022a. *Welcome to i-Tree Landscape!* https://landscape.itreetools.org/.

i-Tree. 2022b. *The Harvest Carbon Calculator.* i-Tree. https://harvest.itreetools.org/.

i-Tree. 2022c. *i-Tree Eco methods, model description, and journal articles.* https://www.itreetools.org/support/resources-overview/i-tree-methods-and-files/i-tree-eco-resources.

i-Tree. 2022d. *Welcome to i-Tree Canopy!* https://canopy.itreetools.org/.

Janowiak, M., W.J. Connelly, K. Dante-Wood, G.M. Domke, C. Giardina, Z. Kayler, K. Marcinkowski, et al. 2017. *Considering forest and grassland carbon in land management*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-95.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey. 2003. National scale biomass estimators for United States tree species. *Forest Science*, 49: 12–35.

Johnson, E.A. 1992. *Fire and vegetation dynamics: Studies from the North American boreal forest*. Cambridge University Press. https://doi.org/10.1017/CBO9780511623516.

Johnson, T.G. (ed.). 2001. *United States timber industry—an assessment of timber product output and use, 1996.* Gen. Tech. Rep. SRS-45. U.S. Department of Agriculture, Forest Service.

Kashian, D.M., W.H. Romme, D.B. Tinker, M.G. Turner, M.G, Ryan. 2006. Carbon storage on landscapes with stand-replacing fires. *Bioscience*, 56(7): 598–606. https://doi.org/10.1641/0006-3568(2006)56[598:CSOLWS]2.0.CO;2.

Keane, R.E., K. Gray, V. Bacciu. 2012a. *Spatial variability of wildland fuel characteristics in northern Rocky Mountain ecosystems*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/RMRS-RP-98.

Keane, R.E., K. Gray, V. Bacciu, S. Leirfallom. 2012b. Spatial scaling of wildland fuels for six forest and rangeland ecosystems of the northern Rocky Mountains, USA. *Landscape Ecology*, 27: 1213–1234. https://doi.org/10.1007/s10980-012-9773-9.

Keith, H., D. Lindenmayer, A. Macintosh, B. Mackey. 2015. Under what circumstances do wood products from native forests benefit climate change mitigation? *PloS ONE*, 10(10): e0139640. https://doi.org/10.1371/journal.pone.0139640.

Khalil, M.A.K., and R.A. Rasmussen. 1990. The global cycle of carbon monoxide: Trends and mass balance. *Chemosphere,* 20(1-2): 227–242. https://doi.org/10.1016/0045-6535(90)90098-E.

Koch, F.H., and J.R. Ellenwood. 2020. *Sustainable forest indicator 3.16*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/research/sites/default/files/2022-03/Indicator3.16.pdf.

Koch, F.H., and K.M. Potter. 2020. *Sustainable forest Indicator 3.15.* U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/research/sites/default/files/2022-03/Indicator3.15.pdf.

Krajnc, N. 2015. *Wood fuels handbook*. Food and Agriculture Organization of the United Nations. https://agris.fao.org/agris-search/search.do?recordID=XF2017001919.

Leskinen, P., G. Cardellini, S. González-García, E. Hurmekoski, R. Sathre, J. Seppälä, C. Smyth, et al. 2018. *Substitution effects of wood-based products in climate change mitigation*. From Science to Policy 7. European Forest Institute. https://doi.org/10.36333/fs07.

Leturcq, P. 2020. GHG displacement factors of harvested wood products: The myth of substitution. *Scientific Reports*, 10(1): 1–9. https://doi.org/10.1038/s41598-020-77527-8.

Liang, S., M.D. Hurteau, A.L. Westerling. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. *Frontiers in Ecology and the Environment*, 16(4): 207–212. https://doi.org/10.1002/fee.1791.

Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: known and unknowns. *Carbon Management,* 2(3): 303–333. https://doi.org/10.4155/CMT.11.24.

Loeffler, D., N. Anderson, K. Stockmann, T. Morgan, N. Tase. 2019. *Carbon stored in harvested wood products from California timberlands: 1952–2017*. Forest Industry Fact Sheet No. 2. https://www.bber.umt.edu/pubs/forest/biomass/Fact-Sheet-CA-Carbon-2019.pdf.

Loehman, R.A., E. Reinhardt, K.L. Riley. 2014. Wildland fire emissions, carbon, and climate: Seeing the forest and the trees—A cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. *Forest Ecology and Management*, 317: 9–19. https://doi.org/10.1016/j.foreco.2013.04.014.

Loudermilk, E.L., R.M. Scheller, P.J. Weisberg, A. Kretchun. 2016. Bending the carbon curve: Fire management for carbon resilience under climate change. *Landscape Ecology*, 32: 1461–1472. https://doi.org/10.1007/s10980-016-0447-x.

Lucey, T., N. Tase, P. Nepal, D. Nichols, K. Sahoo, R. Bergman, A. Gray. In review. Chapter 3: Harvested wood product model synthesis. In *Management and policy effects on forest sector carbon: a synthesis of model approaches to guide projections on the West Coast.* Gen. Tech. Rep. PNW-GTR-XXX. U.S. Department of Agriculture, Forest Service.

Lutes, D.C. 2019. *FOFEM: First Order Fire Effects Model v6.5 user guide*. U.S. Department of Agriculture, Forest Service. http://firelab.org/project/fofem.

Ma, W., C.W. Woodall, G.M. Domke, A.W. D'Amato, B.F. Walters. 2018. Stand age versus tree diameter as a driver of forest carbon inventory simulations in the northeastern U.S. *Canadian Journal of Forest Research,* 48(10): 1135–1147. http://doi.org/10.1139/cjfr-2018-0019.

Marañón-Jiménez, S., J. Castro, A.S. Kowalski, P. Serrano-Ortiz, B.R. Reverter, E.P. Sánchez-Cañete, R. Zamora. 2011. Post-fire soil respiration in relation to burnt wood management in a Mediterranean mountain ecosystem. *Forest Ecology and Management*, 261(8): 1436–1447. https://doi.org/10.1016/j.foreco.2011.01.030.

Marcille, K.C., T.A. Morgan, C.P. McIver, G.A. Christensen. 2020. *California's forest products industry and timber harvest, 2016*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/pnw/publications/california%E2%80%99s-forest-products-industry-and-timber-harvest-2016.

Marland, E., and G. Marland. 2003. The treatment of long-lived, carbon-containing products in inventories of carbon dioxide to the atmosphere. *Environmental Science and Policy*, 6(2): 139–152. https://doi.org/10.1016/S1462-9011(03)00003-0.

Marland, E.S., K. Stellar, G. Marland. 2010. A distributed approach to accounting for carbon in wood products. *Mitigation and Adaptation Strategies for Global Change*, 15: 71–91. https://doi.org/10.1007/s11027-009-9205-6.

Martin, A.R., M. Doraisami, S.C. Thomas. 2018. Global patterns in wood carbon concentration across the world's trees and forests. *Nature Geoscience,* 11(12): 915–920. https://doi.org/10.1038/s41561-018-0246-x.

Marx, L., C. Zimmerman, T. Ontl, M. Janowiak. 2021. *Healthy forests for our future: A management guide to increase carbon storage in Northeast forests.* The Nature Conservancy and Northern Institute of Applied Climate Science. https://www.nrs.fs.usda.gov/pubs/63533.

McCaffrey, S.M., A.G. Rappold, M.C. Hano, K.M. Navarro, T.F. Phillips, J.P. Prestemon, A. Vaidyanathan, et al. 2022. Chapter 7: Social considerations: health, economics and risk communication. In Peterson, D.L., S.M. McCaffrey, T. Patel-Weynand (eds.). *Wildland fire smoke in the United States: A scientific assessment*. Springer. https://www.fs.usda.gov/research/publications/book/wildfiresmoke/wildfiresmokefull.pdf.

McCauley, L.A., M.D. Robles, T. Woolley, R.M. Marshall, A. Kretchun, D.F. Gori. 2019. Large-scale forest restoration stabilizes carbon under climate change in Southwest United States. *Ecological Applications*, 29(8): e01979. https://doi.org/10.1002/eap.1979.

McGlynn, E., K. Harper, S. Li, M. Berger. 2019. *Reducing climate policy risk: Improving certainty and accuracy in the U.S. land use, land use change, and forestry greenhouse gas inventory: Technical appendix*. https://www.climateworks.org/wp-content/uploads/2019/09/Technical-Appendix-FINAL.pdf.

McKeever, D.B. 2009. *Estimated annual timber products consumption in major end uses in the United States, 1950–2006*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/FPL-GTR-181.

McKeever, D.B., and R.H. Falk. 2004. Woody residues and solid waste wood available for recovery in the United States, 2002. In Gallis, C. (ed.). *European COST E31 Conference: Management of recovered wood—recycling bioenergy and other options: Proceedings.*

McKeever, D.B., and J.L. Howard. 2011. Solid wood timber products consumption in major end uses in the United States, 1950–2009: A technical document supporting the Forest Service 2010 RPA assessment. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/FPL-GTR-199.

McPherson, E.G., and J.R. Simpson. 1999. *Carbon dioxide reduction through urban forestry*. U.S. Department of Agriculture, Forest Service. http://www.actrees.org/files/Research/co2reduction.pdf.

Meigs, G.W., D.C. Donato, J.L. Campbell, J.G. Martin, B.E. Law. 2009. Forest fire impacts on carbon uptake, storage, and emission: The role of burn severity in the Eastern Cascades, Oregon. *Ecosystems*, 12: 1246–1267. https://doi.org/10.1007/s10021-009-9285-x.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, et al. 2013. Anthropogenic and natural radiative forcing. In Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, et al. (eds.). *Climate change 2013: The physical science basis*. *Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Nelson, M.D., K.H. Riitters, J.W. Coulston, G.M. Domke, E.J. Greenfield, L.L. Langner, D.J. Nowak, et al. 2020. *Defining the United States land base: A technical document supporting the USDA Forest Service 2020 RPA assessment*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/NRS-GTR-191.

Nowak, D.J. 1994. Understanding the structure. *Journal of Forestry*, 92(10): 42–46. https://www.nrs.fs.usda.gov/pubs/jrnl/1994/ne_1994_nowak_001.pdf.

Nowak, D.J. 2021. *Understanding i-Tree: 2021 summary of programs and methods*. U.S. Department of Agriculture, Forest Service. https://www.itreetools.org/documents/650/i-Tree_Methods_gtr_nrs200-2021.pdf.

Nowak, D.J., and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution,* 116(3): 381–389. https://doi.org/10.1016/S0269-7491(01)00214-7.

Nowak, D.J., and E.J. Greenfield. 2010. Evaluating the national land cover database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. *Environmental Management*, 46(3): 378–390. https://doi.org/10.1007/s00267-010-9536-9.

Nowak, D.J., J.C. Stevens, S.M. Sisinii, C.J. Luley. 2002. Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture*, 28(3): 113–122.

Nowak, D.J., D.E. Crane, J.C. Stevens, R.E. Hoehn, J.T. Walton. 2008. A ground-based method of assessing urban forest structure and ecosystem services. *Aboriculture & Urban Forestry*, 34(6): 347–358. https://www.fs.usda.gov/treesearch/pubs/19526.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, E. Lapoint. 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution,* 178: 229–236. https://doi.org/10.1016/j.envpol.2013.03.019.

Ohmann, J.L., and M.J. Gregory. 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, USA. *Canadian Journal of Forest Research*, 32(4): 725–741. https://doi.org/10.1139/x02-011.

Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, et al. 2020. Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, 118(1): 86–101. https://doi.org/10.1093/jofore/fvz062.

Oswalt, S.N., W.B. Smith, P.D. Miles, S.A. Pugh. 2019. *Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment.* U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-97.

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, et al. (2011). A large and persistent carbon sink in the world's forests, 1990–2007. *Science*, 333(6045): 988–993. https://doi.org/10.1126/science.1201609.

Pearson, T., S. Walker, S. Brown. 2005. *Sourcebook for land use, land-use change and forestry projects.* The World Bank Group. https://openknowledge.worldbank.org/bitstream/handle/10986/16491/795480WP0Sourc0CF0Projects00PUBLIC0.pdf.

Pearson, T.R.H., S.L. Brown, R.A. Birdsey. 2007. *Measurement guidelines for the sequestration of forest carbon*. U.S. Department of Agriculture, Forest Service. https://www.nrs.fs.usda.gov/pubs/gtr/gtr_nrs18.pdf.

Permar, W., W. Wang, V. Selimovic, C. Wielgasz, R.J. Yokelson, R.S. Hornbrook, A.J. Hills, et al. 2021. Emissions of trace organic gases from western U.S. wildfires based on WE-CAN aircraft measurements. *JGR Atmospheres,* 126(11): e2020JD033838. https://doi.org/10.1029/2020JD033838.

Pingoud, K., and F. Wagner. 2006. Methane emissions from landfills and carbon dynamics of harvested wood products: The first order decay revisited. *Mitigation and Adaptation Strategies for Global Change*, 11: 961–978. https://doi.org/10.1007/s11027-006-9029-6.

Pingoud, K., K.E. Skog, D.L. Martino, M. Tonosaki, Z. Xiaoquan. 2006. Chapter 12: Harvested wood products. In *2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_12_Ch12_HWP.pdf

Prescott, C.E., and S.J. Grayston. 2023. TAMM review: Continuous root forestry—Living roots sustain the belowground ecosystem and soil carbon in managed forests. *Forest Ecology and Management*, 532: 120848. https://doi.org/10.1016/j.foreco.2023.120848.

Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, et al. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, 31(8): 28–58. https://doi.org/10.1002/eap.2433.

Prichard, S.J., E.M. Rowell, A.T. Hudak, R.E. Keane, E.L. Loudermilk, D.C. Lutes, R.D. Ottmar, et al. 2022. Fuels and consumption. In Peterson, D.L., S.M. McCaffrey, T. Patel-Weynand (eds.). *Wildland fire smoke in the United States: A scientific assessment*. Springer. https://www.fs.usda.gov/research/publications/book/wildfiresmoke/wildfiresmokefull.pdf.

Prisley. S., J. Bradley, M. Clutter, S. Friedman, D. Kempka, J. Rakestraw, E. Sonne Hall. 2021. Needs for small area estimation: Perspectives from the U.S. private forest sector. *Frontiers in Forests and Global Change,* 4*.* https://www.frontiersin.org/articles/10.3389/ffgc.2021.746439/full.

Puettmann, M. 2020a. *CORRIM report*: *Life cycle assessment for the production of Pacific Northwest softwood lumber*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020b. *CORRIM report: Life cycle assessment for the production of Southeastern softwood lumber*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020c. CORRIM report: *Life cycle assessment for the production of Inland Northwest softwood lumber*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020d. *CORRIM report: Life cycle assessment for the production of Northeast–Northcentral softwood lumber*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020e. *CORRIM report: Life cycle assessment for the production of PNW softwood plywood*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020f. *CORRIM report: Life cycle assessment for the production of Southeast softwood plywood*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M. 2020g. *CORRIM report: Life cycle assessment for the production of oriented strandboard production*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M., and J. Salazar. 2018. *Cradle to gate life cycle assessment of North American particleboard production*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M., and J. Salazar. 2019. *Cradle to gate life cycle assessment of North American medium density fiberboard production*. Consortium for Research on Renewable Industrial Materials.

Puettmann, M., Bergman, R., Oneil, E. 2016. *Cradle-to-gate life cycle assessment of North American hardboard and engineered wood siding and trim production.* Consortium for Research on Renewable Industrial Materials.

Pugh, S.A., J.A. Turner, E.A. Burrill, W. David. 2018. *The Forest Inventory and Analysis database: Population estimation user guide*. U.S. Department of Agriculture, Forest Service. https://www.fia.fs.usda.gov/library/database-documentation/current/ver80/FIADB%20Population%20Estimation%20user%20guide_11_2018_final_revised_02_2019.pdf.

Raymond, C.L., S. Healey A. Peduzzi P. Patterson. 2015. Representative regional models of post-disturbance forest carbon accumulation: Integrating inventory data and a growth and yield model. *Forest Ecology and Management,* 336: 21–34. https://doi.org/10.1016/j.foreco.2014.09.038.

Rebain, S. A., E.D. Reinhardt, N.L. Crookston, S.J. Beukema, W.A. Kurz, J.A. Greenough, D.C.E. Robinson, et al. 2010 (rev. 2022). *The fire and fuels extension to the Forest Vegetation Simulator: Updated model documentation*. U. S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/fmsc/ftp/fvs/docs/gtr/FFEguide.pdf.

Reinhardt, E., and N.L. Crookston. 2003. *The Fire and Fuels Extension to the Forest Vegetation Simulator*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/RMRS-GTR-116.

Reinhardt, E.D., R.E. Keane, J.K. Brown. 1997. *First Order Fire Effects Model: FOFEM 4.0 user's guide*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/INT-GTR-344.

Riley, K.L., I.C. Grenfell, M.A. Finney, J.M. Weiner. 2021. TreeMap, a tree-level model of conterminous US forests circa 2014 produced by imputation of FIA plot data. *Scientific Data*, 8: 11. https://doi.org/10.1038/s41597-020-00782-x.

Rothstein, D.E., Z. Yermakov, A.L. Buell. 2004. Loss and recovery of ecosystem carbon pools following stand-replacing wildfire in Michigan jack pine forests. *Canadian Journal of Forest Research*, 34: 1908–1918. https://doi.org/10.1139/x04-063.

Rüter, S., and M. Lundblad. 2019. Chapter 12: Harvested wood products. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch12_HarvestedWoodProducts.pdf.

Sathre, R., and J. O'Connor. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy*, 13(2): 104–114. https://doi.org/10.1016/j.envsci.2009.12.005.

Shaw, J.D., and A. Gagnon. 2019. Field note: A new conversion of Forest Inventory and Analysis data for use in the Forest Vegetation Simulator. *Journal of Forestry*, 118(3): 307–312. https://doi.org/10.1093/jofore/fvz050.

Simmons, E.A., M.G. Scudder, T.A. Morgan, E.C. Berg, G.A. Christensen. 2016. *Oregon's forest products industry and timber harvest 2013 with trends through 2014*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/PNW-GTR-942.

Simmons, E.A., L. Rymniak, T.A. Morgan, K. Marcille, G. Lettman, G. Christensen. 2019. Oregon forest products industry and timber harvest, 2017: Highlights and summary data tables. Bureau of Business and Economic Research, Forest Industry Research Program.

Skog, K. 2001. *Carbon emissions and sequestration from harvested wood—estimation methods and issues*. Unpublished presentation.

Skog, K.E. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal*, 58(6): 56–72. https://www.fs.usda.gov/treesearch/pubs/31171.

Skog, K.E., and G.A. Nicholson. 2000. Carbon sequestration in wood and paper products. In Joyce, L.A., and R. Birdsey (eds.). 2000. *The impact of climate change on America's forests: A technical document supporting the 2000 USDA Forest Service RPA Assessment.* Gen. Tech. Rep. RMRS-GTR-59. U.S. Department of Agriculture, Forest Service.

Smith, J.E., L.S. Heath, and J.C. Jenkins. 2003. *Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests.* U.S. Department of Agriculture, Forest Service.

Smith, J.E., L.S. Heath, K.E. Skog, R.A. Birdsey. 2006. *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/research/treesearch/22954.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh. 2009. *Forest resources of the United States, 2007*. Washington, DC: U.S. Department of Agriculture, Forest Service.

Smith, J.E., G.M. Domke, C.W. Woodall. 2021. Predicting downed woody material carbon stocks in forests of the conterminous United States. *Science of The Total Environment,* 803(7): 150061. https://doi.org/10.1016/j.scitotenv.2021.150061.

Soimakallio, S., H. Fehrenbach, S. Sironen, T. Myllyviita, N. Adballa, J. Seppälä. 2022. *Fossil carbon emission substitution and carbon storage effects of wood-based products*. Reports of the Finnish Environment Institute. https://helda.helsinki.fi/handle/10138/342930.

Sommers, W.T., R.A. Loehman, C.C. Hardy. 2014. Wildland fire emissions, carbon, and climate: Science overview and knowledge needs. *Forest Ecology and Management*, 317: 1–8. https://doi.org/10.1016/j.foreco.2013.12.014.

Spies, T.A., E. White, A. Ager, J.D. Kline, J.P. Bolte, E.K. Platt, K.A. Olsen, et al. 2017. Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. *Ecology and Society*, 22(1): 25. https://doi.org/10.5751/ES-08841-220125.

Stockmann, K.D., N.M. Anderson, K.E. Skog, S.P. Healey, D.R. Loeffler, G. Jones, J.F. Morrison. 2012. Estimates of carbon stored in harvested wood products from the United States forest service northern region, 1906–2010. *Carbon Balance and Management*, 7: 1. https://doi.org/10.1186/1750-0680-7-1.

Thompson, M.P., K.L. Riley, D. Loeffler, J. Haas. 2017. Modeling fuel treatment leverage: Encounter rates, risk reduction, and suppression cost impacts. *Forests,* 8(12): 469. https://doi.org/10.3390/f8120469.

UNFCCC. 2021. *CDM methodology booklet.* United Nations Framework Convention on Climate Change. https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf#AR_ACM0003.

Urbanski, S. 2014. Wildland fire emissions, carbon, and climate: Emission factors. *Forest Ecology and Management*, 317: 51–60. https://doi.org/10.1016/j.foreco.2013.05.045.

Urbanski, S.P., S.M. O'Neill, A.L. Holder, S.A. Green, R.L. Graw. 2022. Chapter 5: Emissions. In Peterson, D.L., S.M. McCaffrey, T. Patel-Weynand (eds.). *Wildland fire smoke in the United States: A scientific assessment*. Springer. https://www.fs.usda.gov/research/publications/book/wildfiresmoke/wildfiresmokefull.pdf.

U.S. Census Bureau. 2011. *Cartographic boundary files*.

U.S. Census Bureau. 2017. *2010 census urban area FAQs.* https://www.census.gov/programs-surveys/geography/about/faq/2010-urban-area-faq.html.

U.S. DOE. 1992. Part I appendix: Forestry. In *Technical guidelines: Voluntary Reporting of Greenhouse Gases (1*605(b)) Program. U.S. Department of Energy, Office of Policy and International Affairs. https://ghginstitute.org/wp-content/uploads/2020/05/January2007_1605b-GHG-TechnicalGuidelines.pdf.

U.S. DOE. 2007. *Technical Guidelines: Voluntary Reporting of Greenhouse Gases (1605(b)) Program*. U.S. Department of Energy, Office of Policy and International Affairs. https://ghginstitute.org/wp-content/uploads/2020/05/January2007_1605b-GHG-TechnicalGuidelines.pdf.

U.S. EPA. 1991. *Non-road engine and vehicle emission study-report*. U.S. Environmental Protection Agency, Office of Mobile Services.

U.S. EPA. 2011. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2009*. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2009.

U.S. EPA. 2018a. *eGRID*. U.S. Environmental Protection Agency. https://epa.gov/egrid/data-explorer.

U.S. EPA. 2018b. *Construction and demolition debris generation in the United States, 2015*. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2018-09/documents/construction_and_demolition_debris_generation_in_the_united_states_2015_final.pdf.

U.S. EPA. 2020a. *National overview: Facts and figures on materials, wastes and recycling*. U.S. Environmental Protection Agency. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#NationalPicture.

U.S. EPA. 2020b. *Waste Reduction Model (WARM).* U.S. Environmental Protection Agency. https://www.epa.gov/warm/versions-waste-reduction-model-warm#15.

U.S. EPA. 2022. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020*. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.

USDA Forest Service. 2005. *Forest inventory mapmaker, RPA table, and FIADB download files.* U.S. Department of Agriculture, Forest Service.

USDA Forest Service. 2010a. *Forest Inventory and Analysis field methods for phase 3 measurements.* Version 5.0. U.S. Department of Agriculture, Forest Service.

USDA Forest Service. 2010b. Forest Inventory and Analysis National Core field guide: Field data collection procedures for phase 2 plots. Version 5.0. U.S. Department of Agriculture, Forest Service.

USDA Forest Service. 2021. *Forest carbon status and trends.* U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Carbon%20Status%201.4.22.pdf.

USDA Forest Service. 2022a. Carbon. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/managing-land/sc/carbon.

USDA Forest Service. 2022b. *Forest Inventory and Analysis database*. U.S. Department of Agriculture, Forest Service.

USDA Forest Service. 2022c. Forest Vegetation Simulator (FVS). U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/fvs/whatis/fvs_carbon.shtml.

USDA Forest Service. 2022d. *Missoula Fire Sciences Laboratory: Welcome to the Fire Lab.* U.S. Department of Agriculture, Forest Service. http://www.firelab.org/science-applications/fire-fuel/111-fofem.

USDA Forest Service. 2022e. *Pacific Northwest Research Station: Fuel and Fire Tools (FFT).* U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/pnw/tools/fuel-and-fire-tools-fft.

USDA Forest Service. 2022f. Forest Inventory and Analysis National Program, FIA library: Database documentation. U.S. Department of Agriculture, Forest Service.

Verrill, S.P., V.L. Herian, H.N. Spelter. 2004. *Estimating the board foot to cubic foot ratio*. FPL-RP-616. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/FPL-RP-616.

Walker, S.M., T. Pearson, S. Brown. 2014. *Winrock sample plot calculator spreadsheet tool.* Winrock International. https://winrock.org/document/winrock-sample-plot-calculator-spreadsheet-tool/.

Walker, S.M., L. Murray, T. Tepe. 2016. *Allometric equation evaluation guidance document.* Winrock International. https://winrock.org/wp-content/uploads/2018/08/Winrock-AllometricEquationGuidance-2016.pdf.

Walker, S.M., T.R.H. Pearson, F.M. Casarim, N. Harris, S. Petrova, A. Grais, E. Swails, et al. 2018. *Standard operating procedures for terrestrial carbon measurement.* Winrock International. https://winrock.org/document/standard-operating-procedures-for-terrestrial-carbon-measurement-manual/.

Westfall, J.A., C.W. Woodall, M.A. Hatfield. 2013. A statistical power analysis of woody carbon flux from forest inventory data. *Climate Change,* 188: 919–931. https://doi.org/10.1007/s10584-012-0686-z.

Westfall, J.A., J.W. Coulston, G.G. Moisen, G.G., H.-E. Andersen (eds.). 2022. Sampling and estimation documentation for the enhanced Forest Inventory and Analysis program: 2022. General Technical Report. NRS-GTR-207. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/NRS-GTR-207.

Westfall, J.A**.**, J.W. Coulston, A.N. Gray, J.D. Shaw, P.J. Radtke, D.M. Walker, A.R. Weiskittel, et al. 2023. *A national-scale tree volume, biomass, and carbon modeling system for the United States*. General Technical Report. WO-104. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-104.

Williams, C.A., H. Gu, T. Jiao. 2021. Climate impacts of U.S. forest loss span net warming to net cooling. *Science Advances*, 7(7). https://doi.org/10.1126/sciadv.aax8859.

Winn, M.F., L.A Royer, J.W. Bentley, R.J. Piva, T.A. Morgan, E.C. Berg, J.W. Coulston. 2020. *Timber products monitoring: unit of measure conversion factors for roundwood receiving facilities*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/treesearch/pubs/60116.

Woodall, C.W., and V.J. Monleon. 2008. *Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program*. U.S. Department of Agriculture. https://www.fs.usda.gov/treesearch/pubs/13615.

Woodall, C.W., L.S. Heath, G.M. Domke, M.C. Nichols. 2011. *Methods and equations for estimating aboveground volume, biomass and carbon for trees in the U.S. forest inventory, 2010.* U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/NRS-GTR-88.

Woodall, C.W., S. Fraver, S.N. Oswalt, S.A. Goeking, G.M. Domke, and M.B. Russell. 2021. Decadal dead wood biomass dynamics of coterminous US forests. *Environmental Research Letters,* 16(10): 104034. https://doi.org/10.1088/1748-9326/ac29e8.

Wright, C.S. 2015. *Piled fuels biomass and emissions calculator*. U.S. Department of Agriculture, Forest Service. https://www.fs.usda.gov/pnw/tools/piled-fuels-biomass-and-emissions-calculator-tool.

Wright, C.S., C.S. Balog, J.W. Kelly. 2009. *Estimating volume, biomass, and potential emissions of hand-piled fuels*. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/PNW-GTR-805.

Xu, H., G. Latta, U. Lee, J. Lewandrowski, M. Wang. 2021. Regionalized life cycle greenhouse gas emissions of forest biomass use for electricity generation in the United States. *Environmental Science & Technology*, 55(21): 14806–14816. https://doi.org/10.1021/acs.est.1c04301.

Appendix 5-A: Background Information

5-A.1 General Background Information

The following subsections provide descriptions of activity data, including examples for forest management, as well as the types of estimations.

5-A.1.1 Activity Data

Activity data are measurements or estimations of the magnitude of human activity resulting in emissions or removals during a given period. In the land use context, these data generally take the form of the area in which an intervention takes place (e.g., area to be reforested), typically reported in hectares; they may also be volume of timber harvested or other metrics that parameterize the magnitude of calculation outputs.

The activity data needed for quantifying GHG flux for each forest management activity discussed in this chapter are described in sections 5.2.1, 5.2.2, 5.2.3, and 5.2.4. In many cases, activity data may already be available as part of existing forest management plans or land cover maps or surveys. Users can also use GPS devices to establish the perimeter of an area of intervention to quantify its total area.

Typically, remote sensing—i.e., data collection by unmanned aerial vehicles (drones), aircrafts, or satellite platforms—is used to obtain activity data through well-established methods. Remote sensing of carbon stocks of forest lands and land-use change continues to advance with large-scale (regional and continental), coarse resolution methods with various degrees of uncertainty and site-specificity. This application of remote sensing is commonly referred to as indirect measurement.

Most of the conventional methods for calculating standing stocks of ecosystem carbon and changes in carbon stocks are based on field measurements, whether translated into published default values or derived from stand inventories. In recent years, the scientific community has increased its interest in how remote sensing data could offer a cost-effective alternative to other data collection techniques and could cover larger areas and collect data more often. Appendix 5-A.7 further discusses the status and prospects of remote sensing.

For smaller, less complex areas, such as a farm woodlot or forest stand, entities may define the boundaries geographically using a GPS device. Entities could also use available surveyors' reports or other maps and photos, such as aerial imagery. Alternatively, online tools (e.g., Google Earth) provide detailed land imagery that entities may use to draw boundaries of proposed sites to estimate the area of intervention. Instructions for using i-Tree Canopy and Google Earth are provided below. Land cover maps and plans with delineated boundaries are especially useful; they may include temporal information, such as activities planned for decades in the future (e.g., planned harvests).

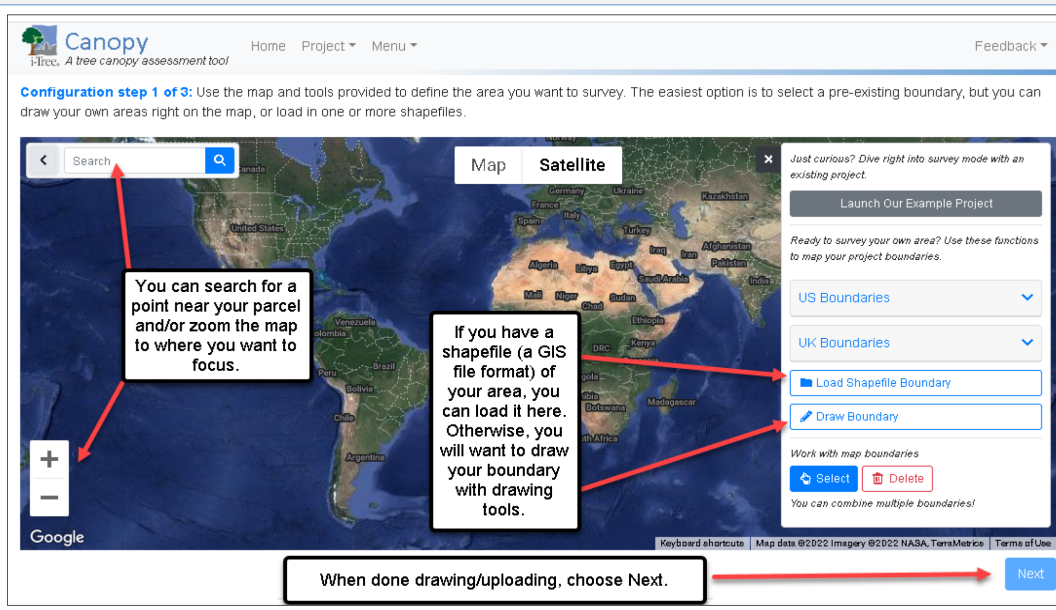
There are a range of options for generating activity data where land cover maps do not exist or where landowners do not clearly understand the total area within each stratum. Other sources of remote sensing data or aerial photography can be useful for any landowner with access to these data but are especially useful for larger land units.

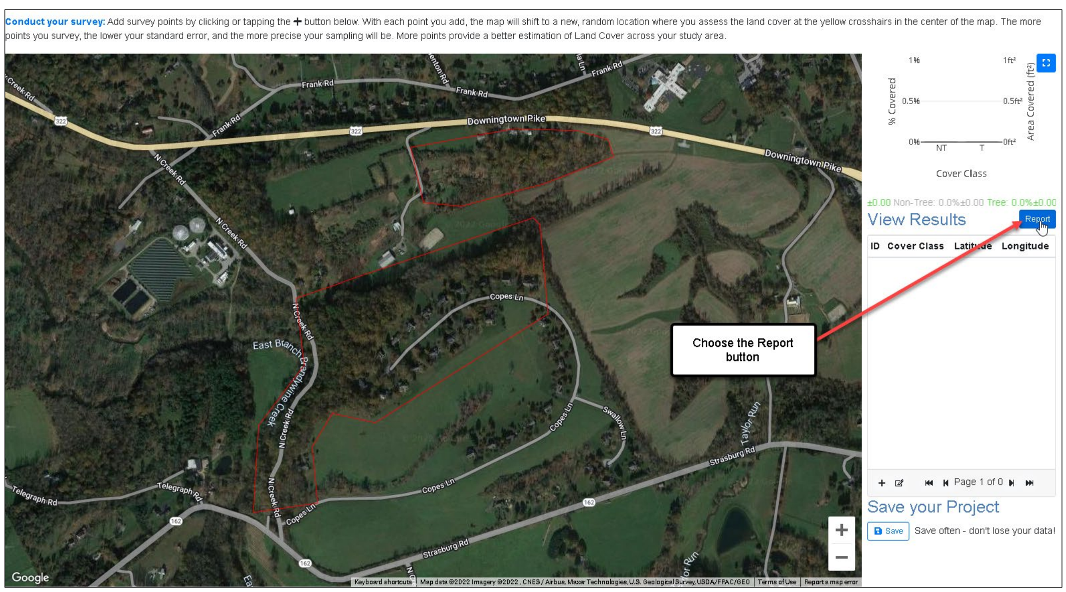
Box 5A-1. Application of GHG Entity Guidelines to Complex Land Ownerships (e.g., Communal Lands, Cooperatives, Some Tribal Lands)

These guidelines work best when applied to land areas where management control is clearly defined and prescribed by a single landowner. It is harder to use them for complex landscapes where individual actors in a communally managed area have more or less freedom to act independently. If actions are agreed upon and prescribed by the communal/cooperative entity in a spatially or temporally explicit plan, the guidelines can be applied as written. Without the ability to precisely identify the spatially explicit activity data necessary—e.g., where individual decisions are more generic and result in a probabilistic management regime rather than being defined by a single management decision or prescription—it may be difficult to follow the guidelines' calculations. Entities may need to use Level 2 or 3 estimation methods to better model the probabilities of various GHG outcomes for the communal entity.

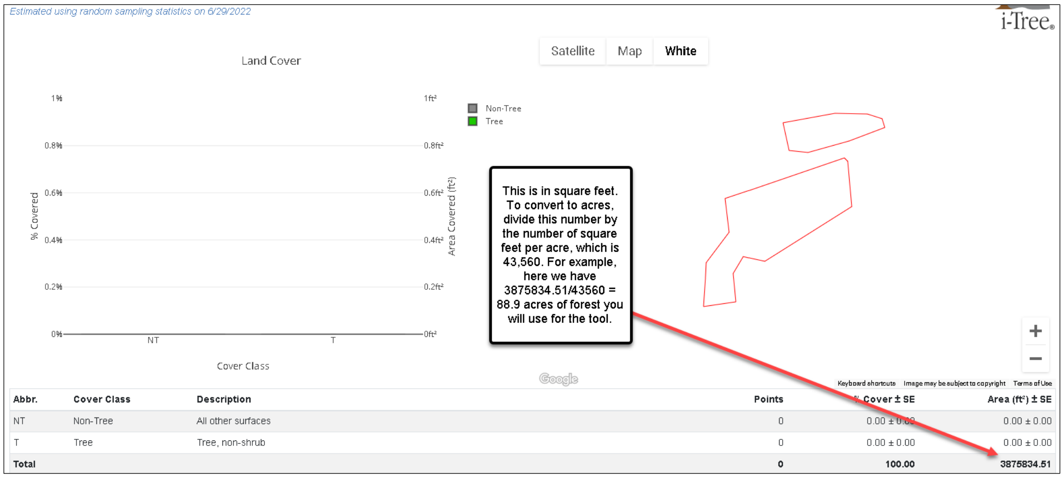
i-Tree Canopy

i-Tree Canopy is a free web tool that is part of the i-Tree suite of tools (i-Tree, 2022d). i-Tree Canopy allows users to estimate land cover and tree cover in areas of interest by interpreting aerial imagery. Entities can use i-Tree Canopy to delineate and estimate the total forest area (activity data) of their forest management activity where data are not currently available, where the property is comprised by a heterogenous mix of forest types, and/or where land cover and stratification is needed. To use i-Tree Canopy, users can follow these basic steps:

Step	Description of Use for i-Tree Canopy
1	Go to the main i-Tree Canopy website (https://canopy.itreetools.org/) and click on the "Get Started" link:
	
2	On the area definition screen, identify the desired area to draw the parcel and visualize it. Use a shapefile (a GIS format file), the address of a nearby point, or zoom in using the "+" button.
	

Step	Description of Use for i-Tree Canopy
3	Draw the polygon and choose Next:
	
4	Select Next repeatedly until the following screen appears, and choose the “report” button:
	

Step	Description of Use for i-Tree Canopy
5	The blank report generated provides the delineated area of the forest parcels.

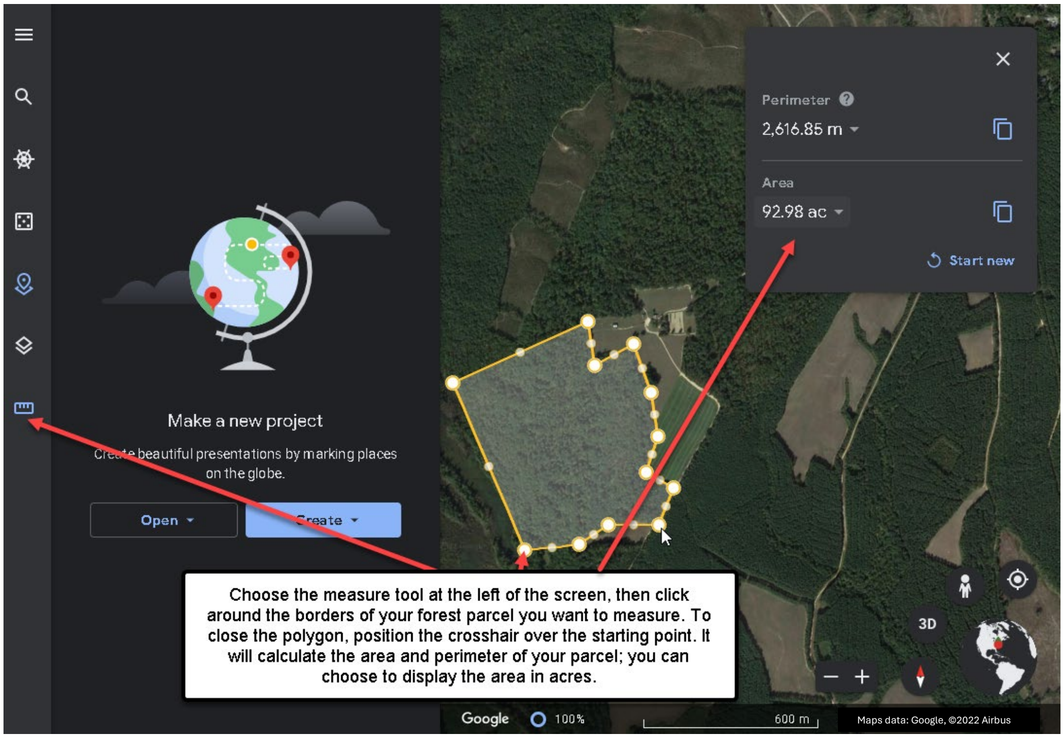
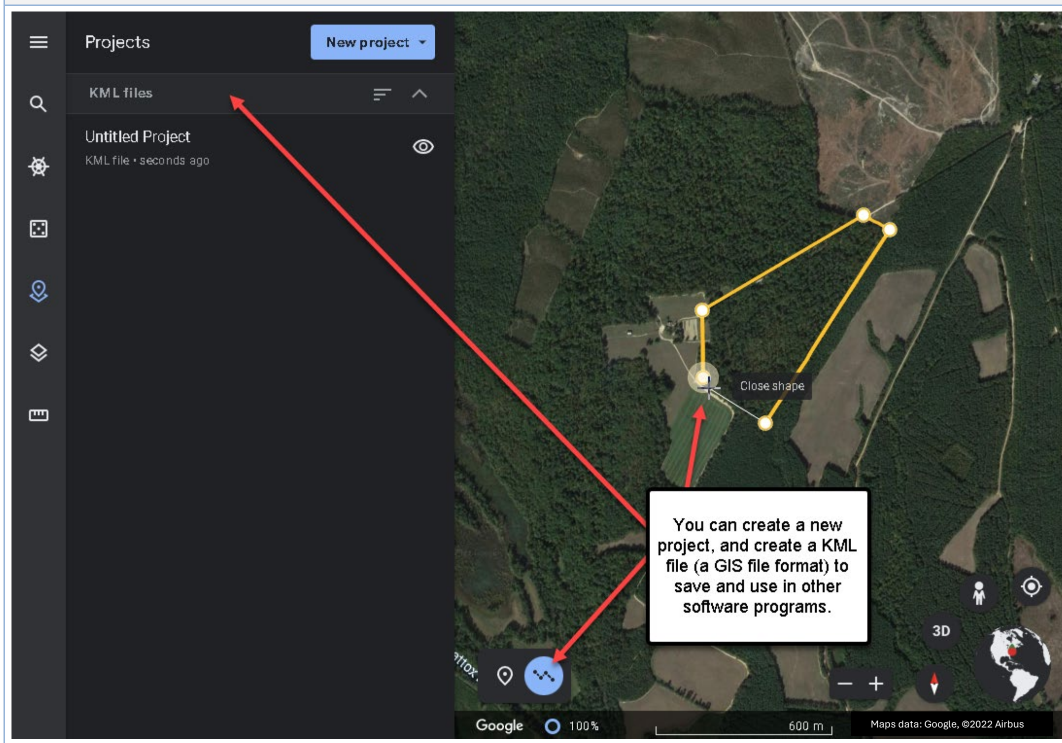


Step	Description of Use for i-Tree Canopy
6	Save the project to recall the boundaries in the future.

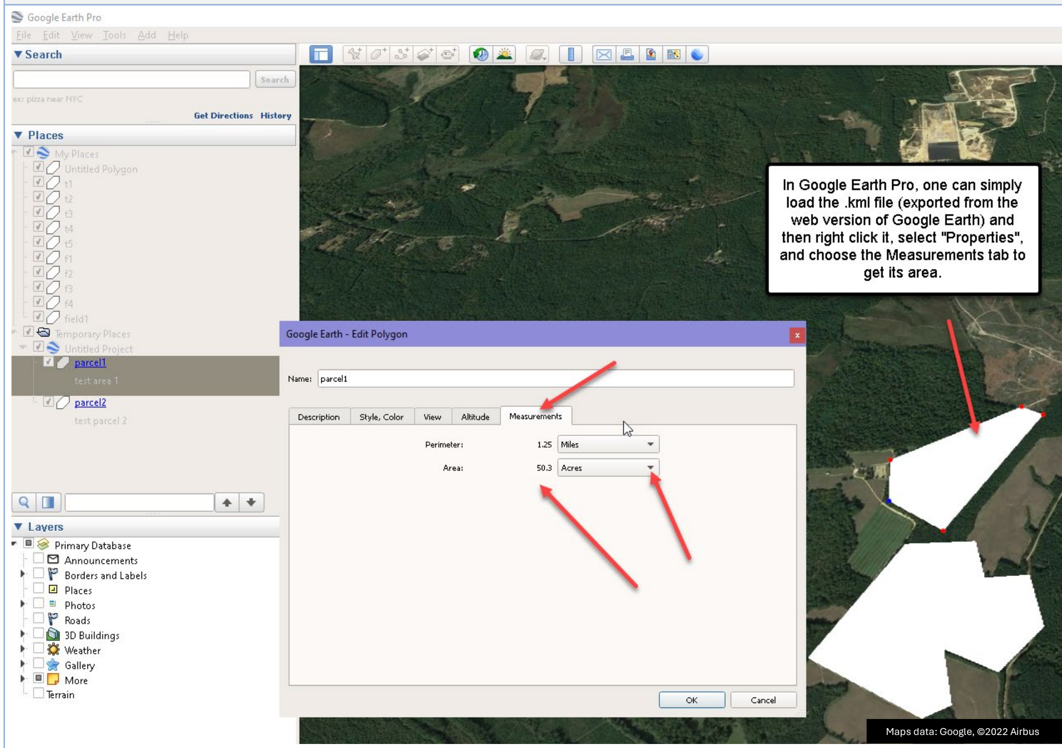
Google Earth

Google Earth is another useful tool for characterizing activity data. The following steps help calculate the area of a forest parcel.

Step	Description of Use for Google Earth
1	Go to earth.google.com and zoom to the area of interest using the search tool ("magnifying glass" button), "+" button, or indicate on the globe:

Step	Description of Use for Google Earth
2	Use the measurement tool—located on the left side of the screen—to calculate the area.
	
3	If needed, create a project and save the parcels.
	

Step	Description of Use for Google Earth
3a	For example, the screenshot below shows a project with two parcels that was exported to Google Earth Pro (a free desktop version of Google Earth).



5-A.1.2 Stock Change vs. Gain–Loss Approaches for GHG Inventories

There are two standard approaches for GHG inventories of forest ecosystems: stock change and gain–loss. Stock change looks at the change in carbon stocks between two points in time (years), then derives annual flux based on the number of intervening years. The stock change approach is more commonly applied where well-established forest sampling programs exist. The gain–loss approach is more common where those data are lacking; it estimates emissions based on the area of carbon stocks that are converted or degraded, rather than directly measuring changes in carbon stocks over time. With this approach, emissions are estimated as the product of the areas of classes of land-use change (characterized as activity data) and the responses of carbon stocks for those classes (characterized as emission factors). This guidance applies the gain–loss approach for silvicultural Level 1 estimates, as described in more detail in Table 5A-1 and the production approach for HWPs.

Table 5A-1. Activity Data and Emission or Removal Factors Definitions and Examples

	Definition	Examples	Quantification Approach
Activity Data	Measurements or estimations of magnitude of human activity resulting in emissions or removals during a given period; most often, the area of land that is converted from one land use to another is the most important type of activity data (IPCC, 2019)	▪ Area planted ▪ Area of forest managed or treated ▪ Volume of timber extracted ▪ Amount of fertilizers ▪ Area burned	▪ Maps ▪ GPS ▪ Google Maps ▪ Remote sensing
Emission or Removal Factor	The average emission rate of a given GHG relative to units of activity (IPCC, 2019)	▪ Forest carbon stocks ▪ Carbon accumulation/ sequestration rate ▪ Volatilization/oxidation rate of fertilizers	▪ Forest inventory: sampling and allometry ▪ Lookup tables ▪ Simulations/modeling

5-A.2 Silviculture Practices and Improved Forest Management

5-A.2.1 Overview of Silviculture Practices and Improved Forest Management

Silviculture practices may result in emissions in other sectors during management activities, such as the use of fossil fuels (e.g., fuel/oil associated with harvesting equipment). As described in section 5.1.5, this chapter does not include methods to calculate the magnitude of emissions from fossil fuels, with a few exceptions.

This appendix explores the initial, generalized categories of silvicultural practices included under the Level 1 approach and describes how to quantify their impacts on carbon storage, accumulation, and emissions, and offers a brief discussion of other silvicultural and improved forest management practices that could be quantified using a Level 3 approach. (Note that chapter 3 also offers guidance on quantifying GHG flux for agroforestry.)

Timber harvesting results in the removal of biomass from the forest system and a change from standing tree to nonstanding tree carbon pools. The carbon removed from the forest may be converted to forest products such as lumber, paper, pulp, and other products that have longer term but variable decomposition rates—and hence longer term and variable emissions over time. In some cases, short-term sinks of products such as paper and pulp HWPs may be at odds with long-term carbon storage in standing forests. Moreover, wood burned for energy is in effect an emission with substitution effects (i.e., avoiding fossil fuel emissions). See appendix 5-A.3 for a description of these relationships, methods for estimating carbon storage in HWPs, and GHG impacts for potential substitution of wood for more emissions-intensive building products or energy sources. See section 5.2.2 for the chosen estimation methods.

5-A.2.2 Extended Rotation

Extended rotation is when a timber harvest is delayed for 1 or more years, potentially resulting in more carbon accumulating in a forest stand (see figure 5A-1). This is a common practice in the “improved forest management” category of carbon projects that seek to sell offsets via the voluntary or compliance carbon markets. These activities typically occur within even-aged forests by deferring harvest to allow the forest stand to grow undisturbed by human activities, which may result in an increase in standing carbon stocks and those stored in HWPs when a harvest does occur. Although extended rotations may include reductions in harvest intensity, this chapter only addresses modification of time intervals. However, many other modifying metrics could be considered, such as economic criteria (e.g., net present values).

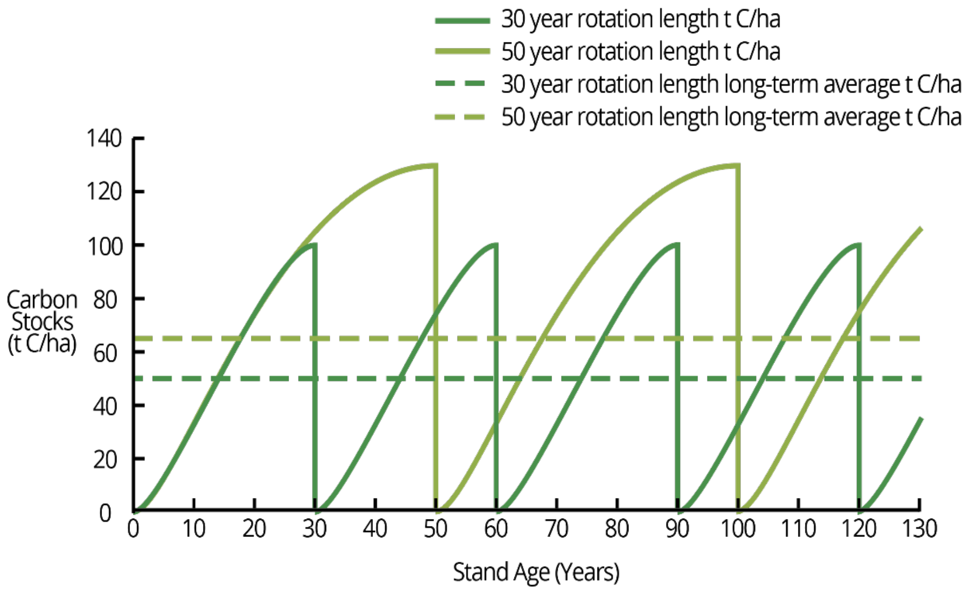


Figure 5A-1. Schematic of Long-Term Average Carbon Storage for Stands Under Different Rotation Lengths

Harvest lengths under conventional silviculture are often based on a careful balancing of biological (i.e., mean annual increment) and economic criteria (i.e., net present value) to maximize yield and investment. When implementing extended rotation to sequester additional carbon, owners may assume some additional costs from stand maintenance and defer profit from timber sales for a few years in favor of sequestering additional carbon and greater future profit, assuming accompanying risks of future disturbance events and highly variable market conditions.

The time for which a rotation is extended beyond its typical length determines the relative benefit of an extended rotation activity: the longer a harvest is deferred, the greater the potential carbon accumulation. However, the relationship between time and carbon accrual is not constant. There may be a point of diminishing returns when considering extended rotation lengths. As figure 5A-2 illustrates, after the initial stages, growth rates and carbon sequestration rates are higher than in the latest stages as the stand ages. Carbon stock continues to increase over time but at a more modest rate. Accordingly, entities should anticipate when peak sequestration/growth will occur to maximize benefits from extending rotation lengths. Further, entities should consider extended rotation activities within the context of overall stand health and resilience: delaying management practices might result in stands becoming overstocked, leading to loss of vigor and resilience. This guidance does not offer explicit analyses of when peak annual accumulation occurs relative to past cumulative accumulation (e.g., stand age 40 in figure 5A-2) among the diversity of forest types included.

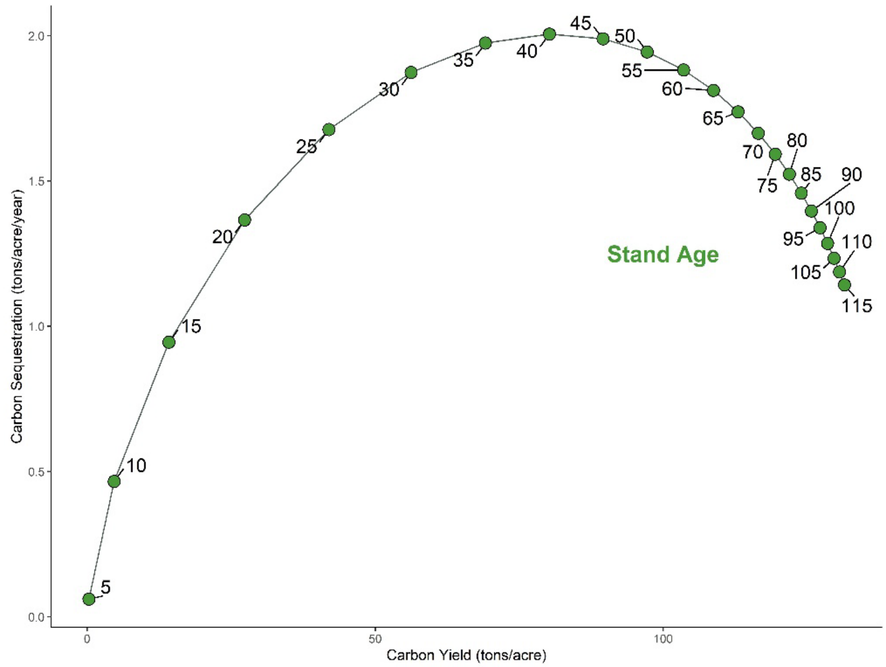


Figure 5A-2. Hypothetical Relationship Between Forest Stand Cumulative Carbon Yield (Tons/Acre) vs. Annual Carbon Sequestration (Tons/Acre/Year) by Stand Age

This guidance offers methods and data for quantifying the benefit of a single extended rotation, as compared to a shorter rotation length, rather than calculating the long-term average carbon benefits over multiple harvests (as shown in figure 5A-2). While the latter would better capture climate benefits as it considers long-term maintenance of the land use, the authors selected the simplified approach in recognition of the timelines relevant to entity owners and the length of time they can realistically commit to management decisions. Rotation cycles are often decades long, and the timelines for accruing long-term benefits over multiple harvests can span generations.

5-A.2.3 Reforestation

Reforestation involves using silvicultural treatments to reestablish forest cover on lands with few or no mature trees. This can be done by preparing the land for natural regeneration and seeding, or by actively planting and protecting seedlings to accelerate the return to forest cover and function. Box 5A-2 discusses definitions of reforestation, but this chapter uses the term “reforestation” for both natural regeneration and human-assisted seeding/planting of trees. The basic methods described in this chapter for quantifying net and annual GHG flux from reforestation do not change based on the extent of human intervention, though the rate at which carbon accumulates can change based on the management intensity of a reforestation project. For example, natural regeneration may only require some basic site preparation, whereas a tree planting project may seek to maximize tree survival through competition control or browse protection which affects the number and growth rate of trees, with important future implications for live tree carbon accumulation and transfers to nonlive tree carbon pools.

Box 5A-2. Reforestation vs. Afforestation

Whether a piece of land was recently a forest or not is important to natural resource sustainability issues and policies that involve tree planting and/or encouraging natural regeneration. Therefore, the terms "reforestation" and "afforestation" are used to distinguish activities based on the condition of land before tree reestablishment.

According to the IPCC (2018), **afforestation** refers to the planting of new forests on lands that historically have not contained forests. **Reforestation** refers to the planting of forests on lands that have previously contained forests but that have been converted to some other use.

These definitions are referenced here because they are commonly used in the literature; however, in terms of carbon accounting for live biomass, there is no practical difference between the two categories. Therefore, this document uses the term "reforestation" for both categories to keep methods approachable for private landowners.

5-A.2.4 Avoided Deforestation

Avoided deforestation is when an intervention prevents an area of forest from being permanently cleared and converted to a nonforest land use (see box 5-1 for a more detailed articulation of the difference between land-use change and land cover change). Where a forest stand is conserved or its harvest intensity is significantly reduced or deferred, its stocks can be maintained, with the stand potentially continuing to sequester carbon in the future.

5-A.2.5 Other Silvicultural Practices/Forest Management Activities

The practices included under Level 1 computations do not reflect the whole breadth of conventional silvicultural treatments (including multi-cohort systems) or the evolving field of climate-smart/adaptive silviculture (ASCC, 2022). Practices such as stand density management (e.g., relative density), species selection, stand structure modification, and site preparation (and other treatments in primarily even-aged stands, as described in table 5A-2) all have impacts on carbon storage and flux. This chapter does not explicitly offer approaches to quantify GHG flux associated with the comingling of all these practices during management operations due to limited data availability and ability to translate those data into user-friendly, Level 1 formats. Future versions of this guidance will seek to expand the set of silvicultural practices covered and potentially take other factors into consideration.

Box 5A-3. Examples of Introductory Resources for Climate-Smart Forest Management

Climate-smart forest management is a set of strategies and management actions intended to support the long-term maintenance of carbon storage benefits from forests and the forest sector. Climate-smart forest management practices bolster forest resilience and provide a broader set of ecosystem services such as water, biodiversity, and soil health (CSF, 2022).

"Forest Management for Carbon Sequestration and Climate Adaptation" (Ontl et al., 2020) offers a menu of adaptation strategies and approaches for forest carbon management based on more than 200 peer-reviewed papers and reports.

"Healthy Forests for Our Future: A Management Guide to Increase Carbon Storage in Northeast Forests" (Marx et al., 2021) introduces and describes 10 forest management practices designed for hardwood forests in New England and New York.

The Northern Institute of Applied Climate Sciences offers several factsheets:

- "Forest Management for Carbon Benefits" (https://www.fs.usda.gov/ccrc/index.php/topics/forest-mgmt-carbon-benefits)
- "Carbon as One of Many Management Objectives" (https://www.fs.usda.gov/ccrc/topics/carbon-one-many-management-objectives)
- "Carbon Considerations in Land Management" (https://www.fs.usda.gov/ccrc/topics/carbon-considerations-land-management)

Those who seek to explore the carbon impacts from silvicultural practices outside those explicitly covered in this guidance, or wish to explore the impacts of more complex, specific, or advanced implementations of the practices that are covered, can consider Level 3 approaches.

Tools and online software platforms are continuing to emerge to support municipal- and entity-scale decision making around climate-smart forestry and policies. A more detailed table of carbon estimation tools and data sources is offered in appendix 5-A.6, and box 5A-4 describes the Land Emissions and Removals Navigator (LEARN) tool, which is designed for municipal-scale GHG inventories and baseline setting.

Box 5A-4. LEARN Tool

The LEARN tool (https://icleiusa.org/LEARN/), developed by the International Council for Local Environmental Initiatives in collaboration with the World Resources Institute's Global Forest Watch and the Woodwell Climate Research Center, was created to help communities estimate their local forests' GHG impacts for forests remaining forests, the effects of reforestation and deforestation, and the effects of selected natural disturbances. LEARN also allows counties and communities to develop a baseline inventory of carbon stocks and stock changes in forests and trees outside forests so they can monitor changes in the GHG impacts of reforestation and deforestation activities, the effects of disturbances occurring within forests remaining forests, and GHG impacts of changes occurring in tree canopies outside forests. The underlying database of removal factors and emission factors was constructed using FIA data and inspired the structure and development of the lookup tables produced for the Level 1 approach employed in this chapter.

Table 5A-2. Common Forest Management Tactics Often Associated With Silvicultural Systems That May Be Modeled Using a Level 3 Approach

Practice	Description	Benefits	Consideration Within This Version of the Guidelines
Stand density management	Controlling the number of trees per unit area in a stand through a variety of techniques, such as underplanting, precommercial thinning, and commercial thinning	Maintains stand at a tree density that provides optimal growing space per tree for best utilization of site resources; allows concentration of site resources on selected trees	▪ Stand density management/thinning are not considered in the Level 1 approach offered in these guidelines, though they are a key area for future refinements. ▪ Under a Level 3 approach, FVS can simulate carbon impacts from thinning practices.

Practice	Description	Benefits	Consideration Within This Version of the Guidelines
Site preparation	Preparing an area of land for forest establishment by removing debris, removing competing vegetation, and/or scarifying soil	Improves survival and initial growth of planted or naturally regenerated seedlings or sprouts; enhances regeneration of desired species; provides conditions favorable for planting of seedlings	Under a Level 3 approach, FVS can simulate impacts from site preparation.
Competing vegetation control	Removing, through chemical or mechanical means, undesirable vegetation that would compete with the desired species being regenerated	Improves survival and growth of desired trees/species	Under a Level 3 approach, FVS can simulate varying mortality rates of desired trees.
Planting	Planting of seedlings by hand or machine to establish a new forest stand; sometimes referred to as "artificial" or "assisted" regeneration	Controls species composition and genetics of newly established stand; controls stocking (density) of trees per unit area for optimal growth/survival	▪ Included under "reforestation." ▪ Enrichment planting (i.e., adding trees to an area with existing forest cover) is not considered. ▪ Agroforestry practices are discussed in chapter 3 (Croplands and Grazing Land Systems). ▪ Planting in urban settings is covered in section 5.2.4 of this chapter.
Natural regeneration	Establishing a new forest stand by allowing/enhancing natural seeding or sprouting	▪ Can result in mix of species ▪ Species that sprout from stumps and roots may rapidly recapture the site ▪ Low-cost relative to planting ▪ May involve less soil disturbance, thereby reducing erosion ▪ Lack of management to control species/density and maximization of growth may result in slower carbon accumulation	Included under "reforestation."
Fertilization	Augmenting site nutrients through the application of nitrogen, phosphorus, or other elements essential to tree growth	Enhances growth of trees; reduces the time for trees to reach merchantable size; eliminates or reduces nutrient deficiencies that would impair forest growth/survival	▪ Not included in Level 1 and 2 options. ▪ Under a Level 3 approach, FVS can simulate fertilizer application on the stand, though fertilizer type and

Practice	Description	Benefits	Consideration Within This Version of the Guidelines
			application loads are limited. ▪ The effects of fertilization are accounted for after growth and mortality have been predicted, so only subsequent cycles are affected.
Selection of rotation length	Choosing the timing of final harvest to control the mix of forest products that can be obtained from the stand (extending a rotation length or deferring a harvest can also serve to sequester additional carbon)	▪ Controls the relative amounts of pulpwood and sawtimber products ▪ Allows landowners to respond to wood product markets by optimizing product mix ▪ Additional years of growth past a baseline rotation length can allow more carbon to be accumulated in the HWPs	This chapter includes Level 1, 2, and 3 options for extended rotation.
Harvesting and utilization	Removal of trees from the forest and cutting and separating logs for forest product markets	▪ Selection of appropriate harvesting systems can provide logs for markets while minimizing damage to residual trees or disturbance of soil. ▪ Choice of harvesting and silvicultural system will impact subsequent regeneration of the stand; systems can be chosen to influence the species composition of the regenerated stand.	This chapter discusses wood harvest, carbon stored in wood products, and climate benefits from substitution of wood products for more emissions-intensive products. The Level 1 approach is described in section 5.2.2.
Fire and fuel load management	Reducing the risk of loss to wildfire by controlling the quantity of fuels in a forest stand using controlled fire or mechanical treatments	Reduces the damage caused by severe wildfires by eliminating excessively high fuel loads; may influence the species composition of the understory	Section 5.2.2 includes Level 1 and 3 options for prescribed burning.
Reducing risk of emissions from pests and disease	Recovering value of timber after damaging events and/or preventing further damage by interrupting spread/intensity of pests/diseases. Reducing risks from emissions from pests and diseases requires managing stand density to keep density below the species-dependent	Salvage harvests recover value in damaged timber by removing it before it is unusable; sanitation harvests prevent spread of pests/diseases.	▪ Level 1 guidance in these guidelines does not include this practice. ▪ Under a Level 3 approach, FVS can simulate carbon impacts from thinning practices.

Practice	Description	Benefits	Consideration Within This Version of the Guidelines
	thresholds defined by research.		
Short-rotation woody crops	Producing merchantable trees in very short periods through intensive management (e.g., genetics, herbicide, fertilization)	Reduces the time for trees to reach merchantable size; often results in HWP with shorter life cycles but with important substitution effects such as bioenergy	This version of the guidelines does not include this practice.

The descriptions in the table above assume forests begin growing at one point in time so that all trees are nearly in the same age cohort. This assumption greatly simplifies the complex array of silvicultural systems that owners consider when they wish to increase the biodiversity, resiliency, or structural diversity of their forest by eliminating those generally applied to uneven-aged systems (e.g., seed tree, shelterwood, or irregular shelterwood). This simplification is an important constraint on the utility of this guidance for many family forest and small corporate landowners.

Silvicultural practices traditionally aim to enhance the provisioning of merchantable timber, which inherently seeks to maximize biomass accumulation in the stems/boles of the trees. However, climate-smart forest management practices instead seek to enhance whole-stand biomass across a variety of carbon pools, species combinations, and stand structures, which can serve as a buffer to global impacts, such as climate change and invasive insects and diseases. These practices also focus on non-timber components, such as limiting soil disturbance or maximizing biodiversity to increase the resilience of forests to future global change.

Many managed forests are subject to various climate-change-related stressors brought on by interacting patterns of rising temperatures, drought, and native or invasive pests and diseases (Koch and Ellenwood, 2020; Koch and Potter, 2020). Forest owners seeking to maximize carbon should do so with an eye toward sustaining long-term resilience on their lands. This means considering climate vulnerability; undertaking long-term maintenance of ecosystem services beyond carbon; and seeking out practices that can support ecosystem adaptation to conditions that may be warmer, drier, fire prone, or subject to extreme weather events.

The carbon stored in forests is always at risk of emission due to episodic disturbances (e.g., wildfires) or chronic health decline (e.g., single-species stands suffering from insect attack)—a risk that varies across space and time. In other words, inadvertent "reversals" of low-carbon-management actions can also lead to emissions. In many cases, there may be synergies among these considerations that help maintain current forest carbon stocks, reduce emission risks to the atmosphere, and/or enhance carbon retention in the long term.

Entity owners should consider these trade-offs when evaluating silvicultural options and consult with professional foresters when considering harvests or other silvicultural practices, no matter what their management objectives are. Fundamentally, entity owners seeking to adopt silvicultural practices are advised to consider those that support the long-term health of the forest (e.g., soil health and tree regeneration/recruitment dynamics) and the other objectives important to individual landowners (e.g., wildlife habitat, aesthetics), rather than focusing solely on live tree carbon accumulation.

5-A.2.6 Background for Lookup Tables

The values for carbon stocks and change in the Excel workbook lookup tables represent the average values of observations and measurements collected from plots that fit the variables used in the analysis: region, forest type group, stand origin, and stand age. In some cases, these values showed the forests are a source of emissions, rather than sequestration. This may be due to a number of reasons:

- The value is a true reflection of carbon dynamics playing out across many Western landscapes. As shown in national analyses by Domke et al. (2020) and Domke and Murray (2021), forests in several intermountain States—most notably Colorado and Montana—have become carbon sources, not sinks, due to the severity and frequency of disturbances in recent years. This trend is also reflected in other summaries of FIA data, such as Hoover and Smith (2021).
- Too few plots matched the particular combination of variables in question and estimates for the plots varied considerably. In these cases, the sampling error is very high and should not be considered an accurate representation of carbon stocks or carbon stock change.
- The selection of variables used to group the FIA plots upon which the Level 1 analysis of carbon was performed does not fully account for the diversity of management practices that may have been adopted at or near the individual plots. This lack of accounting is due to the limitations associated with the approach for applying FIA data instead of model carbon outcomes.

Box 5A-5 below also provides more context on how carbon values are rendered in the FIADB and outlines planned developments in the database outputs.

Box 5A-5. Models and Data for Carbon Pool Estimation: Existing Structures and Future Trajectory for the FIADB

The FIA program provides estimates of DDW, litter, and soil carbon in the FIADB for every condition on national forest inventory plots that meet the definition of forest land (USDA Forest Service, 2022f). These estimates are obtained from models developed using geographic area, forest type, and plot-level attributes (e.g., live tree carbon density, stand age) or auxiliary information (e.g., Digital General Soil Map of the United States). The FIA program has also been measuring DDW, litter, and soil attributes on plots with at least one forest land condition since 2001 (USDA Forest Service, 2022f). These data are collected on a subset of base intensity FIA plots. While the protocols used to sample and measure DDW, litter, and soil attributes have changed over the last 20 years, it is possible to use these observations to estimate status (e.g., carbon stocks) and trends (e.g., carbon stock changes) (Woodall et al., 2021).

The DDW, litter, and soil attributes measured on FIA plots over the last few decades have also been used to develop new methods and models to characterize carbon stocks on plots with these attributes, as well as forested plots without direct measurements of DDW, litter, or soil attributes (Domke et al., 2016, 2017; Smith et al., 2021). These contemporary models not only rely on observations of DDW, litter, and soil attributes from the FIA program, but also include climate variables, physiographic factors, and vegetation type. These models have been used in national GHG reporting (U.S. EPA, 2022) and several State-level reporting activities (Christensen et al., 2021), and will soon replace the models currently used in the FIADB.

5-A.3 Harvested Wood Products

5-A.3.1 HWP Carbon Storage and Emission Inventory

IPCC (2019) provides guidelines for nations to estimate carbon stored and emitted from the HWP pool using one of three tiers (Tiers 1–3) and one of three approaches (production, stock-change, and atmospheric flow), but always using the production approach as part of the reporting. The production approach considers all wood produced by a given entity, regardless of where it is used or disposed of. Thus, while carbon stored in and emitted from HWPs exported outside a reporting country is included, the same from imported HWPs is excluded. Ensuring all nations provide estimates with this production approach means that all HWPs should be comprehensively captured when they are attributed to their country of origin. This helps avoid very challenging accounting, considering that many wood products are exported and serve as inputs to additional processing. Several teams have modeled the IPCC production approach at smaller scales than the entire United States (e.g., Anderson et al., 2013; Loeffler et al., 2019) and some have combined ecosystem and HWP estimates in the same report (e.g., Christensen et al., 2021). To report all emissions, Ganguly et al. (2020) adopted the production approach to account for production emissions and wood products carbon storage in a Washington State study. This appendix guides individual landowners through carbon storage and emission estimation starting with the production approach, where the entity is claiming storage and emissions associated with just HWPs grown from their land.

The HWPs include fuelwood (contained carbon is assumed to be emitted as CO_2 during the year of harvest), as well as logs that are processed into a wide range of primary and secondary wood products. Processing logs into wood products creates "fuel and other" coproducts and a range of feedstock (e.g., pulp chips, sawdust, wood shavings) used to create other HWPs (e.g., paper, paperboard, particleboard, hardboard). Mills burn some of the "fuel and other" material, which is biogenic carbon, to offset some of the electrical and thermal energy required to saw, sort, and dry the primary wood products. Many of the products are used in construction or furniture and have long lives in the products-in-use HWP subpool before they are disposed of. Some products, like paper and packaging, tend to have shorter lives.

There is some continuing debate on how to handle wood bark. Ganguly et al. (2020) assume that most of the bark transported to sawmills, plywood mills, or pulp mills with logs (accounting for 6.06 percent of the logs' volume) is used at the sawmills as hog fuel. This assumption is common among researchers, who consider bark from sawlogs, veneer logs, pulpwood, and fuelwood to be emitted through burning in the year of harvest. The bark, branches, and tops that stay on the forest floor are either burned (through pile or prescribed burning) or assumed to decay over time (Lippke et al., 2011; Ganguly et al., 2018). This assumption means that most of the bark never enters the products-in-use pool, making how and where to count it mainly an issue of holistic emissions accounting. Other authors point to landscaping woodchips as examples of short-lived wood products derived from tree bark (Brandt et al., 2006; Simmons et al., 2016, 2019). As stated in section 5.2.2, because this chapter looks at the overall carbon removals and emissions from forestry activities, carbon transitions from bark harvested in combination with HWP feedstock reported with underbark units should be reflected as changes in either ecosystem and/or HWP pools. Smith et al. (2006) provided ratios to estimate wood bark volume relative to sawlogs and pulpwood (not fuelwood). However, they did not include any bark products in their primary product allocations, and thus bark products are omitted from any estimates of fractions remaining over time.

The 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019) does not provide explicit guidance on how to handle tree bark carbon content in accounting for GHG flux. Although bark is attached to logs brought from the forest to mills, it is not considered part of the underbark feedstock of wood removals or roundwood according to IPCC definitions. Some of this confusion stems from the fact that bark is not part of the typical log volume measures of cubic meters, CCF, or MBF, where scaling log inputs are directly linked to expected final nominal product outputs. Research shows that most tree bark is removed from trees by debarking at mills and burned with energy capture, along with some of the sawdust, trimmings, planer shavings, and other wood removals that constitute fuel and other coproducts (shown in Smith et al., 2006, table 6). In reality, bark and these processing coproducts are often mixed together, depending on their economic values, to optimize boiler operations for onsite energy at the mills. For this chapter, the authors assumed that estimated bark carbon was burned with energy capture in the year it was produced, that bark ratios from Smith et al. (2006) indicate the carbon content, and "mill residue" was used for heating value for this fuel. (Future work may replace this assumption if better information becomes available.) The bark emissions from roundwood (but not logging residues) are used in the LCA potential substitution calculator.

Although it is not included in the harvest carbon calculator results summary, the authors assumed that the estimated bark carbon used in the potential substitution calculator was burned in the year it was cut applying the Smith et al. (2006) table D7 coefficient "a" factors for energy capture. These bark emissions are used in the LCA potential substitution calculator described in section 5.2.2.1. A full discussion of wood bark accounting and assumptions is included in appendix 5-B.2.2. Thoughts for including bark utilization in forest sector carbon accounting are also discussed in more detail in Lucey et al. (in review).

HWP models have traditionally used exponential decay functions to simulate discard of HWPs from use over time and decomposition of discarded HWPs in SWDS. These exponential decay models rely on estimated half-lives—the number of years it takes for half of the amount of material in-use to be discarded. Some researchers (e.g., Bates et al., 2017) have shown that alternative gamma decay functions may better represent the rates at which products in use transition to disposal. The text below describes both of these decay functions.

Box 5A-6. Decay Functions

Decay functions are used to determine the duration of each primary product end use, as well as the actual wood decay rates in landfills. The result of combining these decay rates provides some valuable insight. The disposition distributions cited in this document (U.S. EPA, 2020b) show that 67 percent of solid wood products end up in landfills, where 88 percent remains stored in anoxic environments. Multiplying these percentages shows that 59 percent of the carbon in solid wood products remains permanently stored in landfills. Similarly, 26 percent of paper is disposed of in landfills where 44 percent remains permanently stored, meaning 11 percent of the carbon remains permanently stored.

These are percentages of the primary products that were made, not percentages of the trees that were cut. The modeling recommended here uses regional primary product ratios to account for this additional factor, which determines the percent of delivered logs converted into primary HWPs. The percent of all trees remaining permanently stored is smaller yet, because not all cut trees or all parts of removed trees are transported out of the ecosystem to processing facilities or as fuelwood.

Most U.S. carbon modeling has estimated the end-of-life phase using proportions of disposal going to recycling, landfills, and burning with and without energy capture. Most of the solid wood carbon that goes from products in use to the SWDS subpool (i.e., landfills) remains stored due to the anoxic environment that prevents decay (less so for paper products). Some of the landfilled carbon is emitted as CO_2 and some as CH_4. IPCC recommends that compilers of the AFOLU sector report CO_2 emissions, but the CH_4 emissions are included in a different waste sector. U.S. EPA's WARM notes that almost all U.S. solid and engineered wood waste ends up in dry solid waste landfills or is burned with or without energy recovery. Based on the U.S. EPA WARM report, of all the carbon in wood that ends up in solid waste landfills, only 1 percent of the initial carbon is assumed to be emitted as CH_4 as lifetime landfill emissions. This CH_4 emission, though small, is not captured for energy and gets emitted into the atmosphere (U.S. EPA, 2020b). Appendix 5-B.2 addresses the complexities of the IPCC production approach and provides an example of how to use the Level 1 harvest carbon calculator to estimate HWP stocks and emissions.

The production approach to accounting for HWP carbon storage and emissions is different than an LCA approach. The LCA approach focuses on the fossil CO_2 emissions generated through a product's life cycle and evaluates the environmental impacts from these emissions. More detail on the LCA approach is provided in appendix 5-A.3.2.

5-A.3.2 LCA Overview

The LCA approach is used to estimate the total environmental impacts from producing a product or service. Life cycle analysts first produce a holistic inventory of a product's GHG emissions from raw material extraction to product manufacturing, in some cases extending to products' use and end-of-life processing, also including transportation between stages (illustrated in figure 5A-3). Then, using internationally accepted impact assessment methods, life cycle analysts can quantify the environmental impacts (e.g., global warming impact expressed as CO_2-eq) from input attributes like resources and energy use.

Full LCA with a cradle-to-grave boundary system is beyond the scope of this chapter. The cradle-to-gate LCA adopted instead (see figure 5A-3) quantifies GHG emissions from HWP life stages including harvest, material transportation, and product manufacturing, but omits use and end-of-life stages, and therefore does not calculate total global warming impacts. This chapter does provide insight into HWPs' potential GHG impacts, including potential GHG reduction benefits of substitution wood products for functionally equivalent nonwood products, based on LCA-quantified GHG emissions.

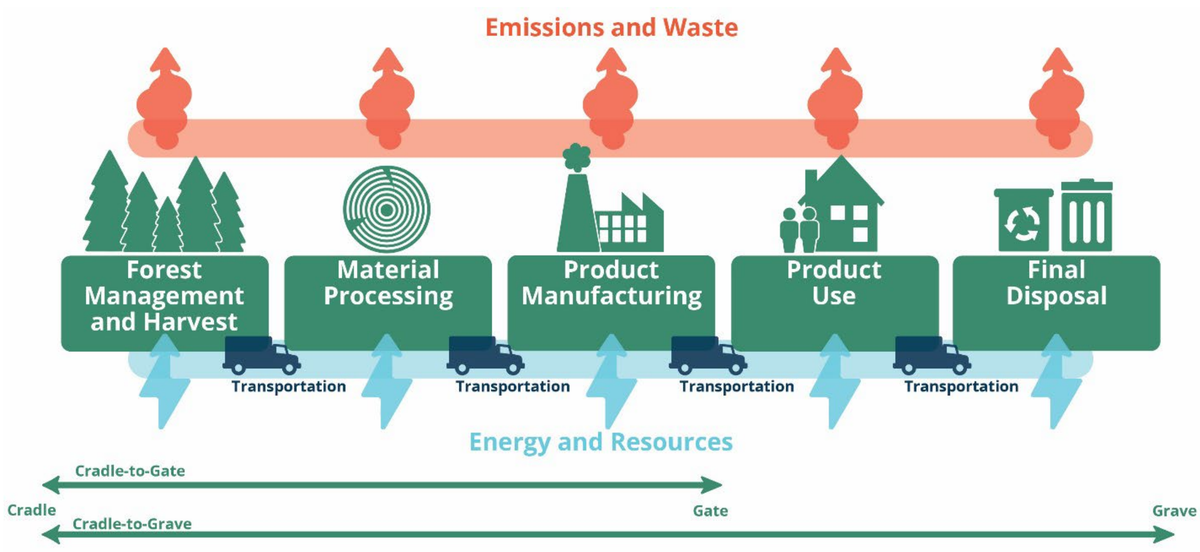


Figure 5A-3. Generic Presentation of Life Cycle Stages of HWPs in LCA Studies

The estimated life cycle GHG emissions of HWPs in this chapter are based on attributional LCA studies by the USDA Forest Products Laboratory and the Consortium for Research on Renewable Industrial Materials. But the estimated GHG reduction benefits associated with substitution of wood for functionally equivalent nonwood products is based on consequential LCA, in which it is assumed that all produced HWPs are used to replace their functionally equivalent nonwood products. The attributional LCA information used in the chapter covers life cycle stages up to the product manufacturing—i.e., cradle-to-gate (or production gate)—system boundary, which includes quantification of GHG emissions from forest management and harvesting operations, transportation of raw wood materials (e.g., logs), and HWP manufacturing activities. The LCA information used in this chapter covers softwood lumber, hardwood lumber, softwood plywood, oriented strandboard, nonstructural panels, and other industrial products, along with energy products from fuelwood. All inputs and outputs are scaled to produce 1 metric ton of each primary product. The flow of biogenic carbon in the LCAs for HWPs is treated separately from fossil CO_2 emissions, as per the requirements of the ISO 21930:2017 standard.

The GHG emissions and estimated substitution factors developed as part of the LCA analysis for this guidance were based on LCA studies performed on different HWPs. All the LCA studies used the TRACI 2.1 impact assessment method, which incorporates GWP values from the IPCC Fourth Assessment Report (i.e., CO_2 = 1, CH_4 = 25, N_2O = 298) (IPCC, 2007, table TS.2). As such, the GWP values used to develop the substitution factor values deviate from IPCC (2013) GWP values presented in chapter 2.

Box 5A-7. LCA-Reported GHG Emissions: 100-Year Approach

After being released, GHGs absorb the heat from solar radiation and cause a warming effect, which can be assessed over the period for which these gases stay in the atmosphere.

An increased abundance of GHGs in the atmosphere, primarily due to the release of fossil-based CO_2 emissions, is increasing global temperature. The net warming impact of GHG emissions is presented as the GWP number in the LCA methods.

A 100-year approach considers the warming impacts of different GHGs up to 100 years once they are released from HWP life stages. Though researchers have compared other approaches with short (20-year) and long (500-year) timeframes, the 100-year approach has been most popular as a balanced choice that allows policymakers to compare different emissions-saving opportunities.

5-A.3.3 Substitution Benefits of HWP

Use of wood instead of functionally equivalent nonwood material avoids significant fossil CO_2 emissions that would have occurred if nonwood products were used (figure 5A-4): for example, wood fuel substituting for fossil-based heat and electricity or transportation fuels, or engineered wood products substituting for concrete and steel structural materials. Because of such avoided emission benefits, HWPs are considered an important part of climate change mitigation strategies and their substitution impacts are widely reported around the world (Leskinen et al., 2018; Hurmekoski et al., 2021; Soimakallio et al., 2022). The LCA-based estimates of GHG emissions of wood products and their functionally equivalent nonwood products can be used to derive the substitution factors are also known as displacement factors. These factors can be further used to quantify total potential benefits from HWP substitutions from forest harvests. This chapter makes no comment about incremental change in HWPs but provides the accompanying Excel workbook that estimates the maximum potential substitution. This quantification of the potential substitution benefits helps inform landowners and policymakers developing forest management and harvesting strategies aimed at realizing higher total GHG reduction benefits.

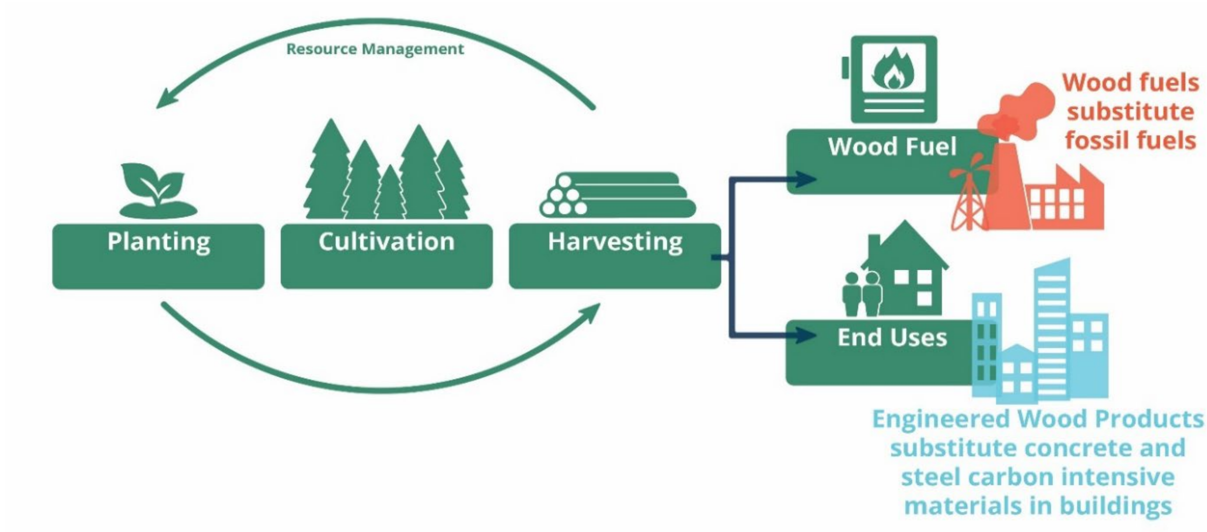


Figure 5A-4. HWP Substitution to Reduce GHG Emissions

5-A.4 Wildfire and Prescribed Fire

Most of the fuel carbon volatilized by combustion is released as CO_2. On average, non-CO_2 products such as CO, CH_4, VOCs, and carbonaceous particles constitute less than 5 percent of volatilized carbon (Urbanski et al., 2022). In addition to CO_2, fires produce the GHGs CH_4 and N_2O (Urbanski, 2014).

Box 5A-8. Impact of Non-GHG Emissions and Particles Produced by Fire

The particles produced by fires also have direct and indirect impacts on climate, but these climate effects are not fully understood and are highly uncertain (Fuzzi et al., 2015). Unlike CO_2, CH_4, and N_2O, these particles reside in the atmosphere for a few days to a couple of weeks before they are removed by cloud droplets or precipitation or transported to the surface by atmospheric turbulence. Non-GHG emissions can have a significant impact on air quality. Carbonaceous particles include fine particulate matter, the main component of wildfire smoke that affects public health (Aguilera et al., 2021; McCaffrey et al., 2022). VOCs and nitrogen oxides (e.g., NO and NO_2), which are also produced by fires, can undergo atmospheric chemical reactions to produce ozone (O_3), another atmospheric pollutant with significant health impacts (Alvarado et al., 2022; McCaffrey et al., 2022).

Indirect emissions result from fire-induced vegetation mortality, which alters subsequent carbon dynamics. In the short term, reduced live vegetation reduces photosynthetic carbon uptake while the decomposition of dead vegetation increases ecosystem release of CO_2 (Marañón-Jiménez et al., 2011). As trees killed by fire continue to decompose, biomass can be converted to atmospheric carbon for many decades postfire (Kashian et al., 2006). However, vegetation recovery and regrowth can compensate for postfire decomposition in as little as 5 to 6 years in some ecosystems, such as high-severity fires in Michigan jack pine and low-severity fires in the Eastern Cascades of Oregon (Rothstein et al., 2004; Meigs et al., 2009). In other ecosystems, carbon emissions might continue to outpace postfire carbon uptake for decades. Prefire carbon stocks may never completely recover in some cases, for example if repeated large, high-severity fires or changes in climate inhibit regeneration (Davis et al., 2019) and drive conversion of coniferous forests to shrub fields (Loehman et al., 2014). Carbon dynamics are affected in the long term through the postfire trajectory of vegetation growth, structure, and species composition, as well as by the timing and severity of future disturbances such as fires, insects, and disease.

Section 5.2.3 reports immediate changes in carbon pools and instantaneous GHG emissions resulting from wildland fire. The methods described in this section offer a starting point for land managers seeking to understand the immediate impacts of low-severity prescribed burns and compare them to GHG impacts from higher severity fire events. The methods presented are limited, though potentially informative in the context of a more indepth analysis of avoided wildfire emissions. Indirect carbon emissions are not addressed. However, the approach used to estimate the immediate fire effects could be extended to provide long-term, postfire trajectories of carbon pools and GHG fluxes.

5-A.5 Urban Forest Management

5-A.5.1 Overview of Urban Forest Management

Like all forests, urban forests—and urban forest management activities—both generate emissions and remove carbon from the atmosphere. Urban forests have some distinctions from peri-urban or rural forests: they are often arranged differently due to the higher density of buildings and other infrastructure, and they are managed for different objectives. Rather than timber production, urban forests are managed for a wide array of functions, including shade, privacy, stormwater runoff mitigation, recreation, noise reduction, urban wildlife habitat, and aesthetic and cultural value. Therefore, the composition of tree species, arrangement of trees, and distribution of trees in urban spaces is highly variable and distinct.

In addition to storing carbon in trees, the urban forest has secondary impacts on atmospheric carbon by affecting carbon emissions from urban and community areas. Tree care and maintenance practices often release carbon back to the atmosphere via fossil fuel emissions from maintenance equipment (e.g., chain saws, trucks, chippers). Thus, some of the carbon gains from tree growth are offset by carbon emissions via fossil fuels used in maintenance (Nowak et al., 2002).

Because they are located where human population is denser and interactions with buildings and other infrastructure are greater, urban trees and forests often have a more direct impact on the built environment. Trees strategically located around buildings can reduce building energy use (e.g., Heisler, 1986) and consequently reduce carbon emissions from fossil-fuel-burning power plants. These energy effects are caused primarily by tree transpiration (lowering of air temperatures), blocking of winds, and shading of buildings and other surfaces. Trees typically lower building energy use in summer but can either lower or increase building energy use in the winter depending upon their location relative to a building.

Emissions from energy-related source categories (e.g., transportation, fuel use, heating fuel use) are typically considered outside the sectoral boundaries of GHG accounting within the AFOLU sector, as described in section 5.1.5. This chapter includes them because of the readily available methods built into the i-Tree suite of tools to account for emissions from urban forest management activities. However, consider sector boundaries and be deliberate in including or excluding non-land use sector carbon flux when establishing accounting and monitoring systems.

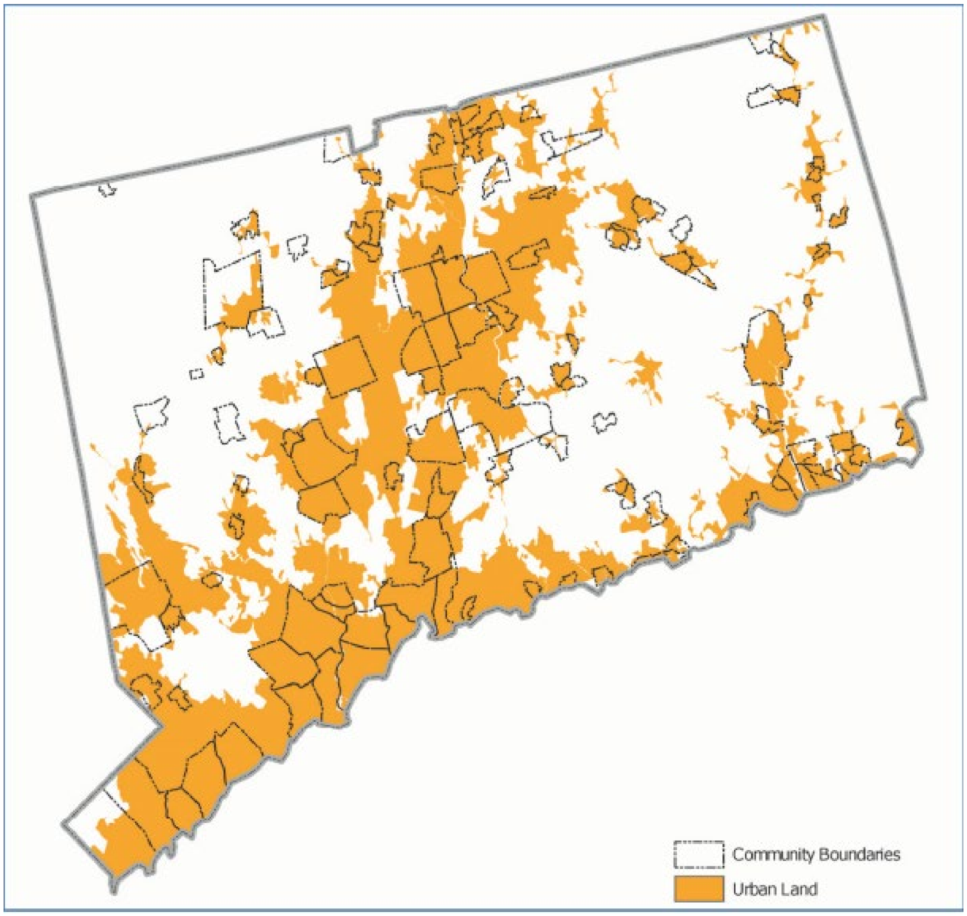
5-A.5.2 Defining Urban Forests

Urban forests: Urban forests are composed of a population of all trees within an area dominated by human settlement. To delimit the extent of an urban forest, the boundaries of the area of interest must be drawn. This boundary issue can be problematic, as people may conceive or describe "urban" differently. For clarity, this chapter defines urban forests as the population of all trees within urban areas and populated places ("communities") as defined by the U.S. Census Bureau based on population density and geopolitical boundaries.

Urban areas: The U.S. Census Bureau (2017) currently defines urban areas as "a densely settled core of census tracts and/or census blocks that meet minimum population density requirements, along with adjacent territory containing non-residential urban land uses as well as territory with low population density included to link outlying densely settled territory with the densely settled core." To qualify as an urban area, a territory must encompass at least 2,500 people, of whom at least 1,500 reside outside institutional group quarters. The Census Bureau identifies two types of urban areas: (1) urbanized areas of 50,000 or more people and (2) urban clusters of 2,500 to 50,000 people (U.S. Census Bureau, 2017). Urbanized areas and urban clusters were derived from census blocks and block groups with population densities of 1,000 people per square mile (386.1 people per square kilometer (250 acres)) in the core and 500 people per square mile (193.1 people per square kilometer) in the surrounding area.

Community areas: In addition to the urban areas described above, the Census Bureau delineates and labels incorporated and unincorporated concentrations of human populations such as cities, towns, villages, and hamlets as census-incorporated and designated places. Like urban areas, these "communities" also define areas where people reside but may include areas with lower population densities than those defined as urban.

Urban and community areas: The geographic areas of the urban and community definitions overlap (see figure 5A-5), and either or both are used to define urban forests as discussed in this chapter. The "urban area" designation is based on population density but may not follow the geopolitical boundaries of cities or towns that most people can relate to. The place or community boundaries follow these geopolitical borders, but often include both rural and urban areas within their limits. Thus, urban forest land may overlap with nonurban forest lands. That is, nonurban forested stands that are measured as part of other programs can exist within urban and community boundaries. Regional- or national-scale assessments of urban forest effects thus might double-count effects in forests. This overlap is estimated as 13.8 percent of urban area or 1.5 percent of forest area in the conterminous United States (Nowak et al., 2013) and is an important consideration for larger-scale assessments.



Source: U.S. Census Bureau, 2011.

Figure 5A-5. Urban and Community Areas in Connecticut

Section 5.2.4 focuses on assessing the carbon effects of urban and community trees and forests in the United States, but the tools it introduces can also be used in rural settings. Urban and community definitions may change from (decadal) census to census, while urban development and official borders change between censuses. Because the tools, models, and methods outlined in section 5.2.4 have been expanded to rural applications, users may draw their own boundaries or use varying combinations of the census geographies to assess their own areas of interest. For example, in rapidly urbanizing regions throughout the United States, users may wish to measure an area that they believe to be urbanizing but that is not officially defined as urban or community.

Trees within urban and community forests—which this chapter collectively calls urban forests—affect the carbon cycle by directly storing atmospheric carbon within the woody vegetation, as well as by affecting the local climate and thereby altering carbon emissions affected by local climatic conditions. Tree maintenance activities also affect carbon emissions in urban and community areas. In addition, urban wood may be harvested and used for an array of biomass-based products or disposed of as waste. For a true accounting of carbon effects, all these factors need to be considered. This chapter focuses on trees (defined as woody vegetation with a diameter of at least 1 inch, or 2.5 cm, dbh), but similar accounting could be conducted for other vegetation.

5-A.6 Carbon Estimation and Data Resources

Table 5A-3 provides a list of data resources and their descriptions. While some resources are described and used within this chapter, others are presented below for informational purposes only. Many of the static, previously published estimates of forest carbon attributes pulled from older databases and summarized in varying ways may still be useful for some applications where contemporary data may be lacking. However, it is beyond the purview of this report to reconcile all previous published estimates with those in this publication, which are meant to connect to emerging inventories and forest carbon quantification techniques.

Table 5A-3. Tool and Data Resources and Descriptions

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
USDA Forest Service Tools Based on FIA Program Data					
EVALIDator	USDA Forest Service FIA program	EVALIDator draws from FIA data to produce estimates with associated sampling errors for user-selected forest attributes: forest area, number of trees, biomass, volume, carbon, growth, removals, and mortality.	EVALIDator produces estimates for different carbon pools (e.g., total forest, aboveground biomass, belowground biomass, soil, standing dead trees). It reports on one attribute at a time, but also can produce ratio estimates (e.g., aboveground live carbon per forested acre). Report results are exported as HTML tables, maps (KML files that can be imported into Google Earth), or SQL code.	USDA Forest Service FIA data	Moderately advanced users who are familiar with FIA data and/or SQL.
Carbon OnLine Estimator (COLE)	USDA Forest Service Research and Development, National Council for Air and Stream Improvement, Inc.	COLE is currently unavailable, but there are ongoing efforts to relaunch it. The COLE suite of web applications allows users to create custom forest carbon outputs from information housed in the FIADB based on user-defined spatial boundaries.	The user defines a spatial area of interest using a map-based selection option. The user can modify the formatting and data retrieval parts of the query, including choosing variables of interest, units, sort options, and analysis functions (e.g., sum, mean, standard deviation). Tabular and graphical outputs can be downloaded in various formats, including Excel and JPEG.	USDA Forest Service FIA data	General audiences.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Carbon Calculation Tool (CCT)	USDA Forest Service Research and Development, U.S. EPA	The CCT executable file runs on a PC and generates State-level annualized estimates of forest carbon stocks and fluxes.	CCT provides tabular summaries by State or national total for five forest ecosystem “reporting” pools from 1990 to present. It also outputs comprehensive pool reports for seven forest ecosystem pools. Both reports contain forest area, timberland area, and timberland live growing stock volume information. The summaries are exported as CSV files.	FORest CARBon Budget Model (FORCARB2) and USDA Forest Service FIA data	Users with an understanding of FIA data collection history and protocol will find it easier to choose between the estimation method options, but overall an easy-to-use tool for a wide audience.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
USDA Forest Service i-Tree suite of online tools and freely available software packages					
i-Tree Eco	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	The Eco downloadable desktop application quantifies the structure of, threats to, benefits of, and values provided by urban forests, including carbon stored and net carbon annually sequestered. It applies user-provided data collected from single trees, complete inventories, or randomly located plots. Users also have the option to collect and automatically upload their field data using the i-Tree Eco Mobile Data Collection system. At a minimum, users need to supply tree species and dbh data for complete inventory projects, and tree species, dbh, percent measured, and percent tree cover for sample-based inventories. Eco comes preloaded with location, species, and multi-year weather and pollution data for the United States and some other countries.	Eco has a variety of reporting options and outputs, from graphs and tables to complete autogenerated reports describing the benefits, effects, and values of an urban forest project. Carbon sequestration is estimated in weight and value per tree per year up to 100 years. The national Urban Forest Inventory and Analysis program inventories and monitors urban trees in more than 30 U.S. cities. For these cities, additional data collection is unnecessary and Eco software does not need to be run, since ecosystem services and values have already been catalogued online.	User-provided inputs combined with carbon estimation methods as described in i-Tree (2022c)	Government agencies, consultants, nonprofits, universities, researchers, volunteers, educators, and advocates undertaking projects ranging from small tree inventories to regional assessments. Users must supply their own inventory data and be able to import or enter field data into i-Tree Eco.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
i-Tree Landscape	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	i-Tree Landscape integrates national landscape and environmental data to support forest management and planning. It allows users to quantify carbon storage and annual sequestration, air pollution removal, hydrologic effects, and dollar value of each benefit for user-defined areas of interest. Users can explore tree canopy, land cover, and basic demographic information for their areas; see how planting trees will increase the benefits provided; and map areas for prioritizing tree planting efforts. Users can also explore local risks to people and forests due to climate change, wildfire, insects and diseases, air pollution, ultraviolet radiation, floods, urban development, and more, and can build tree planting alternatives based on local demographic data, tree cover information, and other variables.	The user creates a planting scenario and generates a PDF report summarizing the project area's planting priorities, tree benefits, and associated reference information.	2011 National Land Cover Database (NLCD), locally supplied high-resolution urban tree cover data (UTC HiRes), and USDA Forest Service FIA data	General audiences with limited data seeking information on total carbon stored and annual carbon sequestration as well as other ecosystem services.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
i-Tree County	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	i-Tree County is based on the data and methods of i-Tree Landscape. The tool allows users to quickly estimate carbon benefits and other ecosystem services and values from trees in an entire U.S. county or smaller area based on user-defined inputs. Users can examine 44 benefits of trees using this tool.	The user can generate a PDF report summarizing estimated benefits and values of the selected county's trees or a custom report based on user-supplied information including the project's area (in acres) and percent tree cover. In addition to the reports, data containing records of the 44 tree benefits for each U.S. county can be downloaded in several tabular and GIS formats.	2011 NLCD, locally supplied high-resolution urban tree cover data (UTC HiRes), and USDA Forest Service FIA data	See i-Tree Landscape description above.
i-Tree Design	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	i-Tree Design (formerly known as the National Tree Benefit Calculator) is a web-based tool for estimating the environmental benefits of individual or multiple trees at the parcel level. Benefits estimated by the calculator include carbon sequestration, decrease in stormwater runoff, air pollution capture and avoidance, and building energy use reduction. The tool works with a Google Maps interface where users view and analyze their property and structures in relation to established trees. Users can produce reports showing current carbon benefits and co-benefits and anticipated benefits from planting more trees.	Projects are saved as .dsgnprj files for future use and reports are exported as PDFs. The report shows total projected carbon benefits and co-benefits over the project's lifetime, benefits trees have provided since they were planted, and monetary benefits per tree.	Google Earth	Homeowners designing a tree planting project who wish to understand the past, current, and future environmental benefit of their trees. The tool is also used by educators, extension agents, landscape architects, energy companies, and tree nurseries.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
i-Tree MyTree	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	The MyTree mobile smartphone application quantifies carbon benefits and other ecosystem services and values for an individual tree or small population of trees. MyTree calculations are based on i-Tree Design. Tree benefits estimated include annual CO2 sequestration, stormwater interception, air pollution removed, energy savings, and avoided emissions, alongside monetary estimates for each benefit. MyTree is linked to the Trillion Trees campaign and the Nature Conservancy's Healthy Trees, Healthy Cities Tree Health Initiative. Trees entered in MyTree and planted for the Trillion Trees campaign are uploaded to the i-Tree Trillion Trees Map. MyTree shares citizen science data entered under Healthy Trees, Healthy Cities' tree health and pest detection protocols for advancing studies on urban tree health.	Users generate a tree benefits report based on details about the tree's location and characteristics.	Google Earth	General audiences with limited data. Designed for use on smartphones and tablets (via browser, without needing to install an app).

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
i-Tree Planting	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	i-Tree Planting (formerly known as the GHG Planting Calculator) is a web-based tool for estimating the environmental benefits of urban tree planting projects. It estimates benefits such as carbon sequestration, decrease in stormwater runoff, air pollution capture, and building energy use reduction.	i-Tree Planting calculates values associated with each tree group over the chosen timeframe based on the selected parameters. Users can save their i-Tree Planting projects and load them for later use. Users can export reports listing avoided building energy emissions and carbon sequestered along with associated monetary values over the project's lifetime.	USDA Forest Service, Davey Tree Expert Company, California Urban Forest Council, Urban Ecos, California Department of Forestry and Fire Protection	Urban foresters and other groups conducting tree planting projects.
i-Tree Canopy	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	i-Tree Canopy is a web-based tool for estimating canopy cover, land use, and associated benefits within a defined area of interest. Uses for the tool include establishing baselines for goal setting, determining areas for tree planting, monitoring change over time, and comparing tree canopy between neighborhoods and school districts. I-Tree Canopy estimates can be used in other i-Tree tools.	i-Tree Canopy project files are saved to the user's hard drive and shared with others working on joint projects. Output consists of a printable report with tables and figures summarizing the cover class type, percent cover, standard error of the cover type estimate, pollution removed, CO_2 storage, annual CO_2 sequestration rate, and monetary value for each source.	GIS data and Google Earth data	Municipal foresters, planners, and urban forestry coordinators, but the tool is also used by educators, volunteers, and neighborhood groups.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
i-Tree Harvest Carbon Calculator	USDA Forest Service, Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, SUNY College of Environmental Science and Forestry	The i-Tree Harvest Carbon Calculator (formerly known as the PRESTO Wood Calculator) is an online tool based on GTR-NE-343 methodologies and lookup tables for HWP pools. It automates GTR-NE-343 calculations and the selection of appropriate tables.	The tool produces tables and reports for four HWP pools based on harvest information supplied by the user: products in use, products in landfills, emitted with energy capture, and emitted without energy capture. The user can view, store, sort, and edit multiple stands for a project and save projects for future use. Stand tables are exported as CSV or Excel files.	GTR-NE-343	Land managers and landowners seeking estimates of postharvest carbon stored in wood products emanating from the lands they manage based on different harvest scenarios.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
USDA Forest Service					
GTR-NE-343	USDA Forest Service Research and Development	The GTR-NE-343 spreadsheet-based carbon calculator contains methods, sample calculations, and regional average tables (i.e., “lookup tables”). Carbon stocks and stock changes in GTR-NE-343 are based on regional averages.	The calculator can be used with or without user-supplied inventory data and provides estimates for average net annual additions to carbon in forests and forest products. Because the lookup tables characterize average carbon values over large areas, the actual carbon values for a stand or project area may differ and should not be used when conditions on a site vary widely. Users who have more specific data on any of the carbon pools, effects of previous land use, etc., may wish to modify figures based on local information and their distinct project needs. The tool features 51 major forest types across 10 geographic regions in the conterminous United States. Users identify the appropriate table for their forest type and look up (or modify) average regional carbon pool values. Separate sets of lookup tables are available for either reforestation/regrowth (i.e., stocks on forest land after clear-cut harvest) or afforestation management activities.	FORCARB2 model, Aggregate Timberland Assessment (ATLAS) model, and USDA Forest Service FIA data	Best suited for users who do not have inventory data and need initial carbon storage and emission estimates for reforestation and afforestation activities and estimates related to harvest, milling, and wood products.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
GTR-NRS-202 (https://www.nrs.fs.usda.gov/pubs/postprint/NRS-GTR-202/)	USDA Forest Service Northern Research Station	GTR-NRS-202 updates ecosystem carbon stock methodologies and estimates developed previously in GTR-NE-343. The new methodologies were developed in support of USDA GHG estimation guidelines for forestry and agriculture published in 2014 in response to direction in the 2008 Farm Bill. GTR-NRS-202 presents new methodologies, updated lookup tables, and information on differences between the new methodologies and those in GTR-NE-343.	The updated ecosystem carbon estimates are meant to be used to get reasonable estimates for major forest types in the conterminous United States. The lookup tables are not summaries of current FIA data and will not capture the inherent variability within forested ecosystems. The estimates are not intended to be used for tree planting scenarios and will likely not provide reliable estimates, at least in the early years following planting. Estimates for harvested wood carbon were not updated for GTR-NRS-202; users need to refer to GTR-NE-343 for these. To use the updated tables for ecosystem carbon, users select tables that best represent the forest type in their areas of interest. Users may apply linear interpolation calculations for values between lookup table values. Likewise, if users have local data for at least one carbon pool, they can substitute their data for values in the lookup tables.	FVS models	Meant for users who need reasonable estimates for major forest types in the conterminous United States.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Forest Vegetation Simulator (FVS)	USDA Forest Service	The FVS suite of software incorporates a family of forest growth simulation models quantifying vegetation change in response to natural succession, disturbances, and management. It replaces ATLAS and FORCARB2 as the modeling framework used to derive the new GTR-NRS-202 carbon lookup tables. FVS recognizes all major tree species and can simulate nearly any type of management or disturbance at any time during the simulation.	FVS consists of a standard model and four model extensions, including the Fire and Fuels Extension (FFE). FFE has a carbon submodel, which allows users to produce carbon reports for ecosystem and HWP pools. A climate extension (Climate-FVS) for the western United States can be used to consider the effects of climate change on forested ecosystems.	FVS Source Code Project and user-supplied inventory data	Due to the complexity of the models and the ability to adjust many user-defined settings, learning FVS requires significant time before first-time users can generate outputs.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Harvested Wood Product Carbon Storage Calculator (HWP Carbon Calculator)	USDA Forest Service	This tool is an online application currently being recoded. Plans are in place to transfer the code base to a USDA Forest Service server, after which the tool will be publicly available online. The HWP Carbon Calculator allows users with yearly harvest data in CCF or MBF and timber product ratios to generate graphics and tables for various measures of carbon storage and carbon emissions. There is a CAL FIRE and Oregon Department of Forestry version of this model, modified from the original USFS model that is currently available online.	Carbon storage outputs include annual harvest and timber product output, annual carbon stocks broken into products in use and solid waste disposal systems, and annual net change in carbon stocks. Carbon emission outputs include annual and total cumulative carbon emitted with and without energy capture.	Multiple sources, including GTR-NE-343, Skog (2008), FPL-GTR-199, McKeever (2009), Skog and Nicholson (2000), and U.S. EPA WARM (U.S. EPA, 2020b)	National Forest System employees produce estimates for the entire National Forest System using USDA annual cut-sold data and support State partners using timber product output data.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Rangeland Carbon Tools	USDA Forest Service, Research and Development	*This tool is under production.* Since no existing USDA Forest Service tool can quantify carbon benefits on nonforest landscapes in the United States, research is underway to provide spatially explicit estimates of carbon in aboveground biomass and SOC for U.S. rangelands. The methods are being adapted based on results from a USDA Forest Service Research Note.	Outputs include estimates for existing nonforest vegetation height, type, and cover; biomass estimates for species assemblages; expanded biomass estimates from stems per unit area to biomass per unit area; and SOC estimates.	LANDFIRE data, Rangeland Vegetation Simulator, Domke et al. (2017), Cao et al. (2019), and FIA forest carbon estimates	National Forest System employees and other land managers.
Resource Planning Act (RPA) Assessment carbon projections	USDA Forest Service, Research and Development	The RPA Assessment includes projections of carbon stocks and fluxes based on FIA data and future climate and socioeconomic scenarios. The carbon projections move the FIA inventory forward in time as influenced by shifts in land use, climate, and demand for roundwood. This keeps both official USDA Forest Service carbon estimates and projections consistent with the FIA inventory.	The Land Use Change model projects future changes among croplands, forests, pastures, rangelands, and developed uses. The Forest Dynamics model projects carbon stock transfers associated with land-use change. The Forest Dynamics model also projects carbon stocks and stock changes for persistent forest land, accounting for forest aging, disturbance effects, climate affects, and forest management. The Forest Resource Outlook Model (FOROM) projects HWP and solid waste disposal site carbon stock and stock change based on inputs including FIA timber product output monitoring data, Food and Agriculture Organization data, and proprietary industry data sources.	RPA Forest Dynamics model, RPA Land Use Change model, FOROM, and Food and Agriculture Organization data	The RPA Assessment's carbon stock and stock change projections are not available as software or an online tool. They are developed by USDA Forest Service scientists and presented in RPA Assessment reports.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Canadian Forest Service					
The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)	The Canadian Forest Service	The CBM-CFS3 wide-ranging decision support tool models forest carbon dynamics at stand and landscape levels for most forest types and geographic regions within Canada. Users can calculate past, present, and future forest ecosystem carbon stocks and stock changes under user-determined forest management scenarios. By default, the database behind the CBM-CFS3 comes with administrative and ecological names and parameters for Canadian jurisdictions and forest ecosystems. However, it can be re-parameterized to apply to jurisdictions and forest ecosystems in other countries. The Canadian Forest Service has also produced a variety of HWP C models that can be used in conjunction with CBM-CFS3 or with harvest data as a stand-alone exercise.	Users can customize model inputs and projects to incorporate different management activities, disturbance types and events, land-use change activities, growth curves, transition rules, and climate projections (temperature only). Assumption Composer tools in the model permit users to modify default project assumptions (or create new assumptions tied to alternate data or parameters), such as growth and yield, stand initialization, growth multipliers, and volume-to-biomass conversion, to simulate a wide range of modeled scenarios for the same imported forest inventory. The model simulates forest ecosystem carbon pools required under the Kyoto Protocol, including aboveground biomass, belowground biomass, litter, dead wood, and SOC using IPCC gain–loss carbon accounting methods.	Carbon Budget Modelling Framework for Harvested Wood Products model and Archive Index Database	Learning the CBM-CFS3 software requires an investment of time for a first-time user to understand the model and generate outputs. A detailed 348-page user guide is available from The Canadian Forest Service.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Tools produced by nongovernment entities					
U.S. Community Protocol's Land Emissions and Removals Navigator (LEARN) tool (https://icleiusa.org/LEARN/)	ICLEI, in collaboration with the World Resources Institute's Global Forest Watch and the Woodwell Climate Research Center through funding from Doris Duke Charitable Foundation and the Climate and Land Use Alliance	This interactive web mapping tool was created to help U.S. communities estimate the local GHG impacts of their forests and trees. It allows counties and communities to develop a baseline and monitoring inventory of carbon stocks and stock changes in forests and trees outside forests. The tool directs users to i-Tree for working with high-resolution images or aerial photos, and to an offline harvested wood calculator if needed.	The tool calculates baseline emissions and removals for a customizable period of time at the community or county level from forests remaining forests; land-use change; and disturbances including harvest, fire, insects, and wind. Outputs are available as a full PDF report as well as a manipulatable Excel table.	FIA program data, data used for the U.S. EPA annual GHG reports, data in the previous version of these USDA guidelines, NLCD data from the U.S. Geological Survey, and NLCD tree canopy cover products from the USDA Forest Service	This tool is freely available to the public. It is simple to use and requires very little input data from users. Users with GIS skills can upload a shapefile to customize the area of interest.

Tool/Data Source Name	Tool Developer	Tool Description/Use	Tool Outputs	Underlying Data Source(s)	Target Audience and Skill Level
Measurement Reporting and Verification (MRV) Toolkit (https://www.goeslab.us/forest-carbon-mrv-tool.html)	Michigan State University	This interactive online software can be used to develop site-specific emission factors from forest inventories using a library of allometric equations and activity data from remote sensing or land-use change data. It produces estimates of emissions and removals for a selection of land use and silviculture situations or scenarios, either as a single practice or as a sequence of linked practices. It supports a complete statistical allocation of a field-based sample plot frame for a forest inventory, or a more simplified use of default values which circumvents the need of a more resource-intensive forest inventory. The MRV Toolkit has a web-mapping interface that allows users to draw project boundaries, parcels or strata within the project, and sample plots on a digital map or other image.	Outputs from this toolkit include two main types of reporting products. The first is estimates of carbon stocks from field inventories at the plot, strata, and project or property levels. The second is reports of calculations using the carbon inventories in chained scenarios of land-use change for the project area to estimate a range of emissions and removals. The toolkit manages all inventory data at the tree level and helps users develop emission factors. It can also use Tier 1 and Tier 2 data, as well as any default values the user provides. The toolkit provides a spatial estimate of the plot allocation for levels of precision and contains an allometric equation library and builder.	Underlying data include all IPCC default values and any Tier 1, 2, or 3 data provided by the user. The toolkit is primarily used with a project or site-specific carbon inventory. All pools are included, but most tools support the live biomass estimation and management.	The target audience is broad, from landowners to professionals. Users need some training and experience with the toolkit. It is suitable for managing data for any international IPCC-compliant project or carbon project registry with verifiers.

NA = Not applicable

5-A.7 Current Status and Future Prospects for Remote Sensing Measurement of Forest Carbon

Within national or regional GHG inventories, remote sensing has been a conventional way to get activity data to quantify the scale of land use and land-use change, though additional information may be needed to attribute drivers of land-use change and/or to determine whether it is a land cover or land-use change (see box 5-1). New platforms are being deployed that are increasing the spatial resolution of these remote sensing systems. These higher resolution products are making remote sensing methods more applicable and practical for smaller stands of forests, including small clusters of trees outside forests. Most of these products are aimed at regional applications for extremely large forest areas or mapping at the scale of counties, States, provinces, or continents. For farm-scale or individual project parcel applications, finer-resolution remote sensing data are needed. In practical terms, field inventory and GIS mapping are still the best practice for entity-scale applications, where properties are 1 square kilometer or smaller.

There are also several sources of up-to-date data that can be interactively traced for updating parcel land-use change using online GIS tools, such as the USDA Cropland Data Layer or Google Maps. Increasingly, commercial vendors are providing web-based mapping tools for overlaying current aircraft or very-high-resolution satellite imagery. Although commercial satellite data are now available at the spatial resolution of aerial photos—as fine as 30 centimeters—they can be expensive for an individual landowner. It is becoming more common for organizations or county governments and organizations to bundle data from several projects across a region, which brings down monitoring costs for individual landowners. Likewise, as organizations look to bundling several properties or parcels, the value of remote sensing data to cover large areas at one time increases. Google Maps, Bing Maps, and other similar platforms offer very-high-resolution image data, at the scale of 0.3 to 3 meters, readily available in a customer-facing form. These platforms present one simple way to informally and interactively view and map parcels and stands of trees on properties.

While methods for using remote sensing for activity data are well established, methods for using it to quantify the carbon stocks of the classes of forest and land-use change are less advanced (e.g., for developing emission factors). Although this field has advanced considerably, remote sensing measurement of tree carbon is currently in a research and development stage for use at the site or parcel scale. Large-scale (regional and continental), coarse-resolution methods have been developed, albeit with various degrees of uncertainty and site-specificity. In the coming years, advancements in very-high-resolution satellite remote sensing, coupled with machine learning, will likely enable direct measurement of carbon stocks. This includes high-spatial-resolution LiDAR, and satellites such as the GEDI mission.

5-A.8 Usage Notes on the Excel Workbook

The Excel workbook is paramount for the methods presented in this chapter. To help facilitate the development of approaches that open forest carbon markets to small parcel owners and/or underserved communities, this revised report includes a Level 1 approach that provides an initial estimate of forest carbon baseline scenario and potential effects of management interventions combining advances in forest ecosystem carbon monitoring, HWP accounting, and fire simulations (wildfire and prescribed). The Excel workbook serves a dual role as a “development workspace” for forest scientists to vet accounting logic and elucidate future refinements while providing basic outputs that the target audience could use immediately. The longer term vision is that with continued research and development investments, the Excel workbook accounting logic could be refined and migrated to a geospatial environment for more robust carbon estimation of parcels following advances in small area estimation, and more dynamic alignment between the tool and Federal data sources (e.g., FIA surveys and remotely sensed information) could be empowered via partners/communities (e.g., open-source code such as R APIs). Through increasing the transparency of accounting logic, data inputs via open-source code, and documentation of methods, it is expected that the leverage provided by USDA partners (e.g., the Natural Climate Solution marketplace, NGOs, States) will accomplish more than the Federal Government alone. Therefore, the Excel workbook is more than a tool—it is transparent accounting logic that can be built upon by the collective forest carbon science/user community in the future.

Appendix 5-B: Method Documentation

5-B.1 Silviculture Practices and Treatments

5-B.1.1 Rationale for Method

These guidelines' use of a Level 1 approach for quantifying impacts from silvicultural practices reflects the standard gain–loss approach to GHG inventories. As discussed in appendix 5-A.1.2., this approach is commonly favored where forest inventories do not exist and relies on published literature or other sources of credible data to assign emissions or carbon removal rates (i.e., emission factors or removal factors) to a measurement or estimate of the magnitude of human activity resulting in emissions or carbon removals (i.e., activity data).

The selection of silvicultural practices was limited to reforestation (natural regeneration or assisted regeneration/planting), extended rotation, and avoided deforestation because they are broadly understood and practiced across U.S. landscapes, their impacts are relatively straightforward to quantify given available data, and the ways in which they sequester additional carbon are well understood. These activities' ecosystem-side impacts could be estimated by combining user-supplied activity data with summarized ecosystem carbon stocks and annualized removal factors (i.e., carbon accrual/stock change), which could be generated using data collected from the FIA's network of permanent plots from across the continental United States (Burrill et al., 2021).

Summarizing these data by U.S. region, forest type group, age class (20-year classes), and stand origin (planted/not planted) yielded emission/removal factors that comprehensively reflect most U.S. forest types and estimate the annual accruals or potential emissions from the selected activities at a scale relevant to entities. This approach offers notable benefits, including the following:

- It applies FIA data to render generalized rates of annual carbon accruals for both planted and naturally regenerated forests across all major U.S. forest types using the NSVB estimators[10] (Westfall et al., 2023) launched in September 2023.
- Drawing from the latest, empirically derived FIA program data (i.e., plot remeasurement data) allows the lookup table values to reflect contemporary forest ecosystem carbon stocks and change, which may be particularly relevant in light of climate-induced changes being observed across U.S. landscapes (Domke et al., 2020).

5-B.1.2 Technical Documentation

Lookup Tables for Silvicultural Practices

The FIA program maintains an extensive array of permanent inventory plots across all land of the United States, with remeasurement generally occurring every 5 to 10 years. The granular forest inventory data are publicly available through a database system known as the FIADB, recently updated to render carbon estimates reflecting the NSVB estimators. The most current information available for each of the 48 conterminous States (typically 6 to 18 months after a panel of inventory plots have been completed within any given State), along with standard FIA estimation routines, was used to generate the lookup tables used in the Excel workbook. Lookup tables were partitioned by certain stand classification variables that allow the user to customize the information to their

[10] https://www.fs.usda.gov/research/programs/fia/nsvb

specific stand. The user must provide values for each of the following classification variables, which are then matched to the corresponding FIA carbon density and flux estimates in the lookup tables:

- Region (see figure 5-4)
- Forest type group (see table 5B-1)
- Stand origin (planted or natural)
- Stand age class (20-year increments to 100 years, then 100+)

The FIADB defines forest type groups by the field "typgrpcd," or forest type group in its condition (COND) table (Burrill et al., 2021). Stand origin ("stdorgcd" in the COND table), identifies stands with clear evidence of artificial regeneration; otherwise, natural regeneration is assumed. Stand age classes ("stdage" in the COND table) are divided into six classes: 0–20, 21–40, 41–60, 61–80, 81–100, and 100+ years. The Excel workbook allows for the user to select an additional class, "Unknown," for any combination of the forest type group, stand origin, age class variables to reflect cases when the user lacks knowledge about the stand being evaluated. Appropriately area-weighted summaries are calculated for all combinations of unknown stock and removal factor values for the stand parameters. Furthermore, each forest type group was reclassified into one of three additional classes—softwood, hardwood, or woodland—and these were used to reflect a user's limited knowledge about the species composition of the stand.

Population-based ratio estimates were generated using FIA estimation techniques to produce average values for carbon density and change components (Westfall et al., 2023). Estimation methods and FIA source table information for generating the lookup tables are contained in SQL scripts used to query and summarize the FIA data, and will accompany these guidelines.

The live tree or standing dead tree carbon stock tables provide carbon density (tons carbon per acre) for trees (≥1 inch dbh) based on the FIADB TREE table's fields "carbon_ag" or "carbon_bg." For each combination of the stand classification variables, mean carbon density is calculated as the quotient formed by the division of the estimate of total carbon stock by the estimate of forest land area for each classification variable combination. The components of gross growth that are used to compute carbon flux in the Excel workbook include survivor growth and ingrowth, and are defined in Westfall et al. (2022) and Pugh et al. (2018). The lookup tables thus contain values of change (tons of carbon change per acre per year) from these components and provide the information that the Excel workbook needs to generate estimates of carbon flux. Mortality is not subtracted: dead trees are assumed to remain in the stand and eventually convert to the DDW pool, which will eventually decay.

In addition to live and dead aboveground and belowground tree carbon, the lookup tables summarize the additional forest ecosystem carbon stocks associated with DDW and litter partitioned by each combination of the stand classification variables. SOC was not included in the annual carbon flux (i.e., emission or removal factors) because current FIA sampling protocols are not sufficient to detect soil carbon stocks and changes, particularly as those changes relate to the impact of specific forest management activities. Similarly, change in standing dead (aboveground or belowground) were not included in change calculations for reasons mentioned in the text. All nontree stock estimates are based on values provided in the FIADB COND table (Burrill et al., 2021). Carbon stock density values (tons carbon per acre) are average values according to region, type, origin, and age class, similar to the approach for tree carbon density. However, the estimates of change for these COND table values are based on average annual net stock change on remeasured plots that are identified as forest at both time 1 and time 2.

The logic behind applying factors from FIA data summaries is as follows.

In the Excel workbook, the user selects (via dropdown menus) the combination of the stand classification variables that corresponds with their knowledge of the stand being evaluated, also providing the acreage of the stand. When values for a user's choice do not exist (i.e., the selected combination of classification variables does not exist in the lookup tables), aggregated values are used as described above. When this occurs, the tool extracts the appropriate carbon density or flux value from the lookup table and applies equation 5B-1 to estimate the total stock, which is then used in equation 5-5. The Excel workbook then generates the Removal Factor, as shown in equation 5B-2; this is used in equation 5-1.

Equation 5B-1: Carbon Stock for Silvicultural Practices

$$Total\ CS_{,rtpa} = (CD_{AGL,rtpa} + CD_{AGD,rtpa} + CD_{BGL,rtpa} + CD_{BGD,rtpa} + CD_{DDW,rtpa} + CD_{L,rtpa} + C_{SOC,rtpa})$$

Where:

Total CS	=	carbon stocks (sum of all carbon pools) (U.S. tons/acre)
CD	=	carbon stocks (U.S. tons/acre)
AGL	=	aboveground live carbon
AGD	=	aboveground dead carbon
BGL	=	belowground live carbon
BGD	=	belowground dead carbon
DDW	=	down dead wood
L	=	litter
SOC	=	soil organic carbon
r	=	region
t	=	forest type group
p	=	planted/natural code
a	=	age class

Equation 5B-2: Change in Carbon Stock from Growth (i.e., Removal Factor)

$$RF_{rtpa} = (\Delta CD_{AGL,T_1,rpta} + \Delta CD_{BGL,T_1,rpta} + \Delta CD_{DDW,T_1,rpta} + \Delta CD_{L,T_1,rpta})$$

Where:

RF	=	sum of all change in carbon stocks (U.S. tons/acre/year)
ΔCD	=	annualized carbon stock change between FIA remeasurement cycles (U.S. tons/acre/year)
AGL	=	aboveground live carbon
BGL	=	belowground live carbon
DDW	=	down dead wood
L	=	litter
r	=	region
t	=	forest type group
p	=	planted/natural code
a	=	age class

Table 5B-1 lists classification variables used in constructing the lookup tables that contain stock and growth factors. Lookup tables contain every combination of these variables that exist in the FIADB in the latest full cycle of inventory data. Values in italics were created for scenarios when the user has limited or no knowledge of the stand characteristics. State groupings for the “region” variable can be found in the provided SQL code and seen in figure 5-4.

Table 5B-1. Classification Variables for the Stocking and Growth Factor Lookup Tables

Region	Forest Type Group		Planted/ Natural Code	Age Class
▪ Central States ▪ Great Plains ▪ Northeast ▪ Northern Lake States ▪ Pacific Northwest Eastside ▪ Pacific Northwest Westside ▪ Pacific Southwest ▪ Rocky Mountain North ▪ Rocky Mountain South ▪ South Central ▪ Southeast	▪ White/red/jack pine group ▪ Spruce/fir group ▪ Longleaf/slash pine group ▪ Loblolly/shortleaf pine group ▪ Other eastern softwoods group ▪ Pinyon/juniper group ▪ Douglas-fir group ▪ Ponderosa pine group ▪ Western white pine group ▪ Fir/spruce/ mountain hemlock group ▪ Lodgepole pine group ▪ Hemlock/Sitka spruce group ▪ Western larch group ▪ Redwood group ▪ Other western softwoods group ▪ California mixed conifer group	▪ Exotic softwoods group ▪ Other softwoods group ▪ Oak/pine group ▪ Oak/hickory group ▪ Oak/gum/cypress group ▪ Elm/ash/ cottonwood group ▪ Maple/beech/birch group ▪ Aspen/birch group ▪ Alder/maple group ▪ Western oak group ▪ Tanoak/laurel group ▪ Other hardwoods group ▪ Woodland hardwoods group ▪ Tropical hardwoods group ▪ Exotic hardwoods group ▪ Nonstocked ▪ Hardwood ▪ Softwood ▪ Woodland ▪ *Unknown*	▪ Planted ▪ Natural ▪ *Unknown*	▪ 0–20 years ▪ 21–40 years ▪ 41–60 years ▪ 61–80 years ▪ 81–100 years ▪ 100+ years ▪ *Unknown*

5-B.2 Harvested Wood Products

5-B.2.1 Rationale for Method

This highest accessibility (Level 1) approach was chosen because it is less complicated and more flexible than existing models and is a suitable model to represent the amount of carbon stored in products in use and in landfills, with their associated emissions.

When forest landowners harvest trees for wood products, a portion of the wood carbon ends up in solid wood products or paper products in end uses, and eventually in landfills. It can remain stored for years or decades. In the past, USDA Forest Service researchers used the WOODCARB II model to estimate aggregate U.S. HWP carbon storage. This modeling system started with national wood consumption to ascertain domestic production. More recently, the National Forest System and State entities have used newer models to adhere to the IPCC production approach at the subnational level (including the USDA Forest Service HWP Carbon Calculator and a similar California variant). The USDA Forest Service built these tools to expand and improve WOODCARB II's calculations, leveraging various fundamental data sources such as Smith et al. (2006), Skog (2008), McKeever (2009) and McKeever and Howard (2011).

The USDA Forest Service built and customized these models to handle actual available data, such as annual cut and sold reports from each national forest and timber product output data (in 40 categories) for States. There is a major point of distinction between the guidance and calculators described below and these more advanced models. The chosen methods are intended for landowners and land managers at the entity level who may not have access to this information about their harvests and how the harvested material will be used. In addition, the more advanced models can combine sequential harvests and multiple vintage year results into cumulative storage and emissions through time. They have more detailed end use allocations, along with a wider range of data on end use half-lives and end-of-life dispositions than prior models—such as splitting out burning with and without energy capture. The time series of recycling and other disposition ratio estimates have also been updated with the U.S. EPA's WARM (U.S. EPA, 2020b) data from 2018 in the USDA Forest Service HWP Carbon Calculator. Moreover, these later models now provide emission estimates in CO_2-eq, recognizing the carbon does not exist as CO_2 in trees or wood products but will end up as CO_2 in the atmosphere. Nonetheless, the emissions modeling could certainly be improved to account for the range of gases produced at various stages of burning and decay.

Ideally, a Level 3 tool would seamlessly integrate ecosystem and HWP modeling with robust estimates and be able to model single-harvest or entire-harvest records with projected future harvests.

5-B.2.2 Technical Documentation

This section provides the detailed technical documentation for methods and calculators described in section 5.2.2. Tables 5B-2 through 5B-6 list factors and fractions used within the HWP lookup tables. The calculator demonstrations describe the growing stock calculator, harvest carbon calculator, and potential substitution calculator, which work together in the Excel workbook to produce results.

Table 5B-2. Factors to Calculate Carbon in Growing Stock Volume: Softwood Fraction, Sawtimber-Size Fraction, and Specific Gravity by Region and Forest Type Group[a]

Region	Forest Type	Fraction of Growing-Stock Volume That Is Softwood[b]	Fraction of Softwood Growing-Stock Volume That Is Sawtimber-Size[c]	Fraction of Hardwood Growing-Stock Volume That Is Sawtimber-Size[c]	Specific Gravity[d] of Softwoods	Specific Gravity[d] of Hardwoods
Northeast	Aspen-birch	0.247	0.439	0.330	0.353	0.428
	Elm-ash-cottonwood	0.047	0.471	0.586	0.358	0.470
	Maple-beech-birch	0.132	0.604	0.526	0.369	0.518
	Oak-hickory	0.039	0.706	0.667	0.388	0.534
	Oak-pine	0.511	0.777	0.545	0.371	0.516
	Spruce-fir	0.870	0.508	0.301	0.353	0.481
	White-red-jack pine	0.794	0.720	0.429	0.361	0.510
Northern Lake States	Aspen-birch	0.157	0.514	0.336	0.351	0.397
	Elm-ash-cottonwood	0.107	0.468	0.405	0.335	0.460
	Maple-beech-birch	0.094	0.669	0.422	0.356	0.496
	Oak-hickory	0.042	0.605	0.473	0.369	0.534
	Spruce-fir	0.876	0.425	0.276	0.344	0.444
	White-red-jack pine	0.902	0.646	0.296	0.389	0.473
Northern Prairie States	Elm-ash-cottonwood	0.004	0.443	0.563	0.424	0.453
	Loblolly-shortleaf pine	0.843	0.686	0.352	0.468	0.544
	Maple-beech-birch	0.010	0.470	0.538	0.437	0.508
	Oak-hickory	0.020	0.497	0.501	0.448	0.565
	Oak-pine	0.463	0.605	0.314	0.451	0.566
	Ponderosa pine	0.982	0.715	0.169	0.381	0.473
Pacific Northwest, East	Douglas-fir	0.989	0.896	0.494	0.429	0.391
	Fir-spruce-m.hemlock	0.994	0.864	0.605	0.370	0.361
	Lodgepole pine	0.992	0.642	0.537	0.380	0.345
	Ponderosa pine	0.996	0.906	0.254	0.385	0.513
Pacific Northwest,	Alder-maple	0.365	0.895	0.635	0.402	0.385
	Douglas-fir	0.959	0.914	0.415	0.440	0.426

Region	Forest Type	Fraction of Growing-Stock Volume That Is Softwood[b]	Fraction of Softwood Growing-Stock Volume That Is Sawtimber-Size[c]	Fraction of Hardwood Growing-Stock Volume That Is Sawtimber-Size[c]	Specific Gravity[d] of Softwoods	Specific Gravity[d] of Hardwoods
West	Fir-spruce-m.hemlock	0.992	0.905	0.296	0.399	0.417
	Hemlock-Sitka spruce	0.956	0.909	0.628	0.405	0.380
Pacific Southwest	Mixed conifer	0.943	0.924	0.252	0.394	0.521
	Douglas-fir	0.857	0.919	0.320	0.429	0.483
	Fir-spruce-m.hemlock	1.000	0.946	0.000	0.372	0.510
	Ponderosa pine	0.997	0.895	0.169	0.380	0.510
	Redwood	0.925	0.964	0.468	0.376	0.449
Rocky Mountain, North	Douglas-fir	0.993	0.785	0.353	0.428	0.370
	Fir-spruce-m.hemlock	0.999	0.753	0.000	0.355	0.457
	Hemlock-Sitka spruce	0.972	0.735	0.596	0.375	0.441
	Lodgepole pine	0.999	0.540	0.219	0.383	0.391
	Ponderosa pine	0.999	0.816	0.000	0.391	0.374
Rocky Mountain, South	Aspen-birch	0.297	0.766	0.349	0.355	0.350
	Douglas-fir	0.962	0.758	0.230	0.431	0.350
	Fir-spruce-m.hemlock	0.958	0.770	0.367	0.342	0.350
	Lodgepole pine	0.981	0.607	0.121	0.377	0.350
	Ponderosa pine	0.993	0.773	0.071	0.383	0.386
Southeast	Elm-ash-cottonwood	0.030	0.817	0.551	0.433	0.499
	Loblolly-shortleaf pine	0.889	0.556	0.326	0.469	0.494
	Longleaf-slash pine	0.963	0.557	0.209	0.536	0.503
	Oak-gum-cypress	0.184	0.789	0.500	0.441	0.484
	Oak-hickory	0.070	0.721	0.551	0.438	0.524
	Oak-pine	0.508	0.746	0.425	0.462	0.516
South Central	Elm-ash-cottonwood	0.044	0.787	0.532	0.427	0.494
	Loblolly-shortleaf pine	0.880	0.653	0.358	0.470	0.516
	Longleaf-slash pine	0.929	0.723	0.269	0.531	0.504
	Oak-gum-cypress	0.179	0.830	0.589	0.440	0.513

Region	Forest Type	Fraction of Growing-Stock Volume That Is Softwood[b]	Fraction of Softwood Growing-Stock Volume That Is Sawtimber-Size[c]	Fraction of Hardwood Growing-Stock Volume That Is Sawtimber-Size[c]	Specific Gravity[d] of Softwoods	Specific Gravity[d] of Hardwoods
	Oak-hickory	0.057	0.706	0.534	0.451	0.544
	Oak-pine	0.512	0.767	0.432	0.467	0.537
Weste	Pinyon-juniper	0.986	0.783	0.042	0.422	0.620
	Tankoak-laurel	0.484	0.909	0.468	0.430	0.459
	Western larch	0.989	0.781	0.401	0.433	0.430
	Western oak	0.419	0.899	0.206	0.416	0.590
	Western white pine	1.000	0.838	0.000	0.376	—

Source: Smith et al. (2006), table 4.

— = no hardwood trees in this type in this region.

[a] Estimates are based on survey data for the conterminous United States from FIADB (USDA Forest Service, 2005) and include growing stock on timberland stands classified as medium- or large-diameter stands. Proportions are based on volume of growing-stock trees.

[b] To calculate fraction in hardwood, subtract fraction in softwood from 1.

[c] Softwood sawtimber are trees at least 22.9 cm (9 in) dbh; hardwood sawtimber is at least 27.9 cm (11 in) dbh. To calculate fraction in less-than-sawtimber-size trees, subtract fraction in sawtimber from 1. Trees less than sawtimber-size are at least 12.7 cm (5 in) dbh.

[d] Average wood specific gravity is the density of wood divided by the density of water based on wood dry mass associated with green tree volume.

[e] West represents an average over all western regions for these forest types.

Table 5B-3. Regional Factors to Estimate Carbon in Roundwood Logs, Bark on Logs, and Fuelwood

Region[a]	Timber Type	Roundwood Category	Fraction of Growing-Stock Volume That Is Roundwood[b]	Ratio of Roundwood (Excluding Fuelwood) to Growing-Stock Roundwood Volume (Including Fuelwood)[c]	Ratio of Fuelwood to Growing-Stock Volume That Is Roundwood[c]	Ratio of Carbon in Bark to Carbon in Wood[d]
Northeast	SW	Sawlog	0.948	0.991	0.136	0.182
		Pulpwood		3.079		0.185
	HW	Sawlog	0.879	0.927	0.547	0.199
		Pulpwood		2.177		0.218
North Central	SW	Sawlog	0.931	0.985	0.066	0.182
		Pulpwood		1.285		0.185
	HW	Sawlog	0.831	0.960	0.348	0.199
		Pulpwood		1.387		0.218
Pacific Coast	SW	Sawlog	0.929	0.965	0.096	0.181
		Pulpwood		1.099		0.185
	HW	Sawlog	0.947	0.721	0.957	0.197
		Pulpwood		0.324		0.219
Rocky Mountain	SW	Sawlog	0.907	0.994	0.217	0.181
		Pulpwood		2.413		0.185
	HW	Sawlog	0.755	0.832	3.165	0.201
		Pulpwood		1.336		0.219
South	SW	Sawlog	0.891	0.990	0.019	0.182
		Pulpwood		1.246		0.185
	HW	Sawlog	0.752	0.832	0.301	0.198
		Pulpwood		1.191		0.218

Source: Smith et al. (2006), table 5.

SW = softwood, HW = hardwood.

[a] "North Central" includes the northern Prairie States and the northern Lake States; "Pacific Coast" includes the Pacific Northwest (west and east) and the Pacific Southwest; "Rocky Mountain" includes Rocky Mountain, north and south; and South includes the Southeast and South Central.

[b] Values and classifications are based on data in tables 2.9, 3.9, 4.9, 5.9, and 6.9 of Johnson (2001).

[c] Values and classifications are based on data in tables 2.2, 3.2, 4.2, 5.2, and 6.2 of Johnson (2001).

[d] Ratios are calculated from carbon mass based on biomass component equations in Jenkins et al. (2003), applied to all live trees identified as growing stock on timberland stands classified as medium- or large-diameter stands in the survey data for the conterminous United States from the FIADB (Alerich et al., 2005; USDA Forest Service, 2005). Carbon mass is calculated for boles from stump to 4-inch (10.2 cm) top, outside diameter.

Table 5B-4. Fraction of Each Classification of Industrial Roundwood (Primary Wood Products)[a]

Region	Category[b] SW/HW	Category[b] SL/PW	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood[c]	Oriented Strandboard	Nonstructural Panels	Other Industrial Products	Wood Pulp	Fuel and Other Emissions
Northeast	SW	SL	0.391	0	0.004	0	0	0.020	0.083	0.072	0.431
		PW	0	0	0	0	0.010	0.016	0	0.487	0.487
	HW	SL	0	0.492	0	0.005	0	0.022	0.038	0.058	0.386
		PW	0	0	0	0	0.293	0.007	0	0.350	0.350
North Central	SW	SL	0.378	0	0	0	0	0.049	0.120	0.084	0.370
		PW	0	0	0	0	0.020	0.009	0	0.486	0.486
	HW	SL	0	0.458	0	0.006	0	0.013	0.044	0.064	0.415
		PW	0	0	0	0	0.361	0.009	0	0.315	0.315
Pacific Northwest, East	SW	All	0.422	0	0.069	0	0	0.001	0.001	0.144	0.363
Pacific Northwest, West	SW	SL	0.455	0	0.089	0	0	0.009	0.073	0.114	0.260
		PW	0	0	0	0	0	0	0	0.500	0.500
	HW	All	0	0.160	0	0.140	0	0.002	0	0.229	0.469
Pacific Southwest	SW	All	0.454	0	0	0	0	0.040	0.036	0.145	0.325
Rocky Mountain	SW	All	0.402	0	0.054	0	0	0.033	0.062	0.153	0.296
Southeast	SW	SL	0.350	0	0.076	0	0	0.027	0.054	0.129	0.364
		PW	0	0	0	0	0.103	0.004	0	0.447	0.447
	HW	SL	0	0.455	0	0.006	0	0.049	0.012	0.087	0.391
		PW	0	0	0	0	0.180	0.002	0	0.409	0.409
South Central	SW	SL	0.324	0	0.130	0	0	0.019	0.023	0.133	0.371
		PW	0	0	0	0	0.135	0.006	0	0.430	0.430
	HW	SL	0	0.434	0	0.023	0	0.025	0.003	0.102	0.413
		PW	0	0	0	0	0.160	0.001	0	0.419	0.419
West[d]	HW	All	0	0.039	0	0.301	0	0.015	0.066	0.147	0.432

Source: Smith et al. (2006), table D6.

[a] Data based on Adams and others (2006).

[b] SW/HW = softwood/hardwood, SL/PW = saw log/pulpwood. Saw log includes veneer logs.

[c] Hardwood plywood fractions are pooled with nonstructural panels when allocating roundwood to the primary products listed in tables 8 and 9 of Smith et al. (2006).

[d] West includes hardwoods in Pacific Northwest, East; Pacific Southwest; Rocky Mountain; North; and Rocky Mountain, South.

Table 5B-5. Total Carbon Fraction Remaining in End Uses: Exponential Function

Year After Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strandboard	Nonstructural Panels	Miscellaneous Products	Paper
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.917	0.881	0.921	0.914	0.930	0.914	0.887	0.895
2	0.887	0.820	0.894	0.880	0.911	0.880	0.828	0.800
3	0.858	0.765	0.868	0.848	0.892	0.848	0.773	0.716
4	0.831	0.716	0.844	0.818	0.874	0.818	0.722	0.640
5	0.806	0.671	0.821	0.789	0.857	0.789	0.674	0.573
6	0.782	0.631	0.799	0.762	0.841	0.762	0.629	0.512
7	0.760	0.594	0.778	0.736	0.825	0.736	0.587	0.458
8	0.739	0.561	0.758	0.711	0.810	0.711	0.548	0.410
9	0.719	0.531	0.740	0.688	0.796	0.688	0.512	0.367
10	0.700	0.503	0.722	0.665	0.782	0.665	0.478	0.328
11	0.681	0.478	0.704	0.644	0.768	0.644	0.446	0.293
12	0.664	0.455	0.688	0.624	0.755	0.624	0.417	0.262
13	0.648	0.433	0.672	0.604	0.742	0.604	0.389	0.235
14	0.632	0.414	0.657	0.586	0.730	0.586	0.363	0.210
15	0.617	0.395	0.643	0.568	0.718	0.568	0.339	0.188
16	0.603	0.378	0.629	0.551	0.707	0.551	0.317	0.168
17	0.589	0.362	0.615	0.535	0.696	0.535	0.296	0.150
18	0.576	0.347	0.602	0.520	0.685	0.520	0.276	0.134
19	0.563	0.334	0.590	0.505	0.674	0.505	0.258	0.120
20	0.551	0.321	0.578	0.490	0.664	0.490	0.241	0.108
21	0.540	0.308	0.566	0.477	0.654	0.477	0.225	0.096
22	0.529	0.297	0.555	0.464	0.645	0.464	0.210	0.086
23	0.518	0.286	0.544	0.451	0.635	0.451	0.196	0.077
24	0.507	0.276	0.534	0.439	0.626	0.439	0.183	0.069
25	0.497	0.266	0.524	0.427	0.617	0.427	0.171	0.062
26	0.488	0.257	0.514	0.416	0.608	0.416	0.159	0.055
27	0.478	0.248	0.504	0.405	0.600	0.405	0.149	0.049
28	0.469	0.240	0.495	0.395	0.591	0.395	0.139	0.044
29	0.460	0.232	0.486	0.385	0.583	0.385	0.130	0.039

Year After Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strandboard	Nonstructural Panels	Miscellaneous Products	Paper
30	0.452	0.225	0.477	0.375	0.575	0.375	0.121	0.035
31	0.444	0.218	0.469	0.366	0.568	0.366	0.113	0.032
32	0.436	0.211	0.461	0.357	0.560	0.357	0.106	0.028
33	0.428	0.204	0.453	0.348	0.553	0.348	0.099	0.025
34	0.421	0.198	0.445	0.340	0.545	0.340	0.092	0.023
35	0.413	0.192	0.437	0.332	0.538	0.332	0.086	0.020
36	0.406	0.186	0.430	0.324	0.531	0.324	0.080	0.018
37	0.399	0.181	0.423	0.316	0.524	0.316	0.075	0.016
38	0.393	0.176	0.416	0.309	0.518	0.309	0.070	0.014
39	0.386	0.171	0.409	0.302	0.511	0.302	0.065	0.013
40	0.380	0.166	0.402	0.295	0.505	0.295	0.061	0.012
41	0.374	0.161	0.396	0.288	0.498	0.288	0.057	0.010
42	0.368	0.157	0.389	0.282	0.492	0.282	0.053	0.009
43	0.362	0.152	0.383	0.275	0.486	0.275	0.050	0.008
44	0.356	0.148	0.377	0.269	0.480	0.269	0.046	0.007
45	0.351	0.144	0.371	0.263	0.474	0.263	0.043	0.007
46	0.345	0.140	0.365	0.258	0.468	0.258	0.040	0.006
47	0.340	0.136	0.360	0.252	0.463	0.252	0.038	0.005
48	0.335	0.133	0.354	0.247	0.457	0.247	0.035	0.005
49	0.329	0.129	0.349	0.241	0.451	0.241	0.033	0.004
50	0.325	0.126	0.344	0.236	0.446	0.236	0.031	0.004
55	0.301	0.111	0.319	0.213	0.420	0.213	0.022	0.002
60	0.280	0.098	0.296	0.193	0.396	0.193	0.015	0.001
65	0.262	0.086	0.276	0.175	0.374	0.175	0.011	0.001
70	0.244	0.077	0.258	0.159	0.353	0.159	0.008	0.000
75	0.229	0.069	0.241	0.145	0.334	0.145	0.006	0.000
80	0.214	0.061	0.225	0.132	0.316	0.132	0.004	0.000
85	0.201	0.055	0.211	0.121	0.299	0.121	0.003	0.000
90	0.189	0.050	0.198	0.111	0.283	0.111	0.002	0.000
95	0.177	0.045	0.186	0.103	0.268	0.103	0.001	0.000
100	0.167	0.040	0.175	0.094	0.254	0.094	0.001	0.000

Year After Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strandboard	Nonstructural Panels	Miscellaneous Products	Paper
100-year average (years 0 to 99)	0.391	0.211	0.408	0.320	0.495	0.320	0.144	0.095

Table 5B-6. Total Carbon Fraction Remaining in SWDS: Exponential Function

Year After Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strandboard	Nonstructural Panels	Miscellaneous Products	Paper
0	—	—	—	—	—	—	—	—
1	0.067	0.096	0.064	0.069	0.056	0.069	0.091	0.085
2	0.091	0.145	0.085	0.096	0.072	0.096	0.138	0.159
3	0.114	0.189	0.106	0.122	0.087	0.122	0.182	0.223
4	0.135	0.228	0.125	0.146	0.101	0.146	0.223	0.278
5	0.155	0.263	0.144	0.169	0.114	0.169	0.261	0.326
6	0.174	0.295	0.161	0.190	0.127	0.190	0.297	0.366
7	0.192	0.324	0.177	0.211	0.139	0.211	0.330	0.401
8	0.208	0.350	0.193	0.230	0.151	0.230	0.360	0.430
9	0.224	0.373	0.207	0.248	0.162	0.248	0.389	0.455
10	0.239	0.395	0.221	0.266	0.173	0.266	0.415	0.475
11	0.253	0.414	0.234	0.282	0.184	0.282	0.440	0.492
12	0.266	0.432	0.247	0.298	0.194	0.298	0.462	0.506
13	0.279	0.448	0.259	0.313	0.204	0.313	0.484	0.517
14	0.291	0.463	0.271	0.327	0.213	0.327	0.503	0.525
15	0.302	0.477	0.282	0.341	0.222	0.341	0.521	0.532
16	0.313	0.489	0.292	0.354	0.231	0.354	0.538	0.536
17	0.323	0.501	0.303	0.366	0.239	0.366	0.554	0.540
18	0.333	0.512	0.312	0.378	0.248	0.378	0.569	0.541
19	0.342	0.522	0.322	0.389	0.255	0.389	0.582	0.542
20	0.351	0.531	0.331	0.399	0.263	0.399	0.595	0.541
21	0.360	0.540	0.339	0.410	0.271	0.410	0.606	0.540
22	0.368	0.548	0.348	0.419	0.278	0.419	0.617	0.538
23	0.376	0.556	0.356	0.428	0.285	0.428	0.627	0.535
24	0.384	0.563	0.363	0.437	0.292	0.437	0.636	0.532
25	0.391	0.569	0.371	0.446	0.298	0.446	0.645	0.529
26	0.398	0.576	0.378	0.454	0.305	0.454	0.652	0.525
27	0.405	0.582	0.385	0.462	0.311	0.462	0.660	0.521
28	0.411	0.587	0.391	0.469	0.317	0.469	0.666	0.516
29	0.418	0.592	0.398	0.476	0.323	0.476	0.672	0.512
30	0.424	0.597	0.404	0.483	0.329	0.483	0.678	0.507
31	0.429	0.602	0.410	0.490	0.334	0.490	0.683	0.502
32	0.435	0.606	0.416	0.496	0.340	0.496	0.688	0.498

Year After Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strandboard	Nonstructural Panels	Miscellaneous Products	Paper
33	0.440	0.610	0.422	0.502	0.345	0.502	0.692	0.493
34	0.446	0.614	0.427	0.508	0.350	0.508	0.697	0.488
35	0.451	0.618	0.433	0.514	0.355	0.514	0.700	0.484
36	0.456	0.622	0.438	0.519	0.360	0.519	0.704	0.479
37	0.460	0.625	0.443	0.524	0.365	0.524	0.707	0.474
38	0.465	0.628	0.448	0.529	0.370	0.529	0.710	0.470
39	0.469	0.631	0.452	0.534	0.375	0.534	0.712	0.466
40	0.474	0.634	0.457	0.539	0.379	0.539	0.714	0.461
41	0.478	0.637	0.462	0.543	0.384	0.543	0.717	0.457
42	0.482	0.640	0.466	0.548	0.388	0.548	0.719	0.453
43	0.486	0.642	0.470	0.552	0.392	0.552	0.720	0.449
44	0.490	0.645	0.474	0.556	0.397	0.556	0.722	0.445
45	0.494	0.647	0.478	0.560	0.401	0.560	0.723	0.442
46	0.497	0.649	0.482	0.564	0.405	0.564	0.725	0.438
47	0.501	0.651	0.486	0.567	0.409	0.567	0.726	0.435
48	0.504	0.653	0.490	0.571	0.413	0.571	0.727	0.431
49	0.508	0.655	0.493	0.574	0.416	0.574	0.728	0.428
50	0.511	0.657	0.497	0.577	0.420	0.577	0.728	0.425
55	0.526	0.665	0.513	0.592	0.438	0.592	0.731	0.411
60	0.539	0.672	0.528	0.605	0.454	0.605	0.732	0.400
65	0.551	0.677	0.541	0.616	0.469	0.616	0.732	0.391
70	0.562	0.682	0.553	0.625	0.483	0.625	0.731	0.383
75	0.572	0.686	0.563	0.633	0.496	0.633	0.730	0.377
80	0.581	0.689	0.573	0.640	0.508	0.640	0.729	0.373
85	0.589	0.691	0.582	0.646	0.519	0.646	0.727	0.369
90	0.596	0.693	0.590	0.652	0.529	0.652	0.726	0.366
95	0.603	0.695	0.597	0.657	0.539	0.657	0.724	0.364
100	0.609	0.697	0.604	0.661	0.548	0.661	0.723	0.362
100-year average (years 0 to 99)	0.459	0.593	0.446	0.513	0.382	0.513	0.643	0.417

Alternate Product Longevity (Decay Functions) Used in the Harvest Carbon Storage Calculator

The IPCC (2006) guidelines use the rate of decay of wood products, assuming "that the amount of woody material in use declines following a first-order decay," but note that "this is not the only assumption possible. Different possibilities include linear decay and more detailed approaches based on studies of the real use of these materials." IPCC (2019) explains that first-order decay—also called exponential decay—"means the annual loss from the stock of products is estimated as a constant fraction of the amount of the stock…. In the case of the 'products in use' pool, the outflow from the pool is calculated based on estimated half-life and associated decay rates of wood products from use assuming first-order decay rates." For countries that do not have their own estimates, IPCC's Tier 1 and 2 approaches provide default half-life values, and associated discard rates, for solid wood products and for paper products (IPCC 2019, table 12.2). Tier 3 methods with country-specific data may differ.

When accounting for carbon in wood products at the entity level, it is not possible to follow the change in stocks of wood products on hand and the rate of decay of products from all previous years, so focus should be on accounting for the lifetime of carbon held in current-year wood products—that is, the fate over time of the carbon held in the current-year output of wood products. The rate at which the discard of wood products and decay in landfills will release the product carbon as CO_2 is required for this estimation. Carbon that is released as CO_2 during the year of harvest must also be accounted for, and a method must be determined to account for the carbon that will be released in subsequent years.

Hoover et al. (2014) recommended methods to estimate carbon storage in wood products using the USDA Forest Service WOODCARB II model (Skog, 2008). The model uses calibrated estimates of product half-lives and limits the decay of wood and paper in landfills. It uses first-order dynamics for both the discard rates of products in use and the fraction of products in landfills that decay. It assumes that some fraction of wood products in landfills is permanent and never oxidized. In discussing uncertainty, Skog (2008) recognizes uncertainty in the fraction of solid wood and paper that is not subject to oxidation in a landfill and uncertainty in the shape of the decay distributions for both products in use and products that will decay in landfills, meaning they may be "different from first order decay" (p. 69).

Marland and Marland (2003) (see also Marland et al., 2010) state that the gamma distribution might be used to better describe the timing of the disposition of wood products over time. This alternate representation is conceptually no more difficult, although it is mathematically more complex than first-order decay. The gamma distribution may more accurately describe the rate at which wood products are removed from service and decay in landfills. In responding to Marland and Marland (2003), Pingoud and Wagner (2006) recognized that the gamma distribution could be closely fitted to many circumstances and that it would provide an elegant mathematical option for describing the real process. In fact, exponential decay (first-order decay) is a special case of the gamma function. The general gamma function has large flexibility and is based on two free parameters, noted as θ and κ in equation 5B-3. When $\kappa = 1$, the gamma distribution reduces to first-order, exponential decay. Another special case of the gamma function, characterized as chi-square, requires two parameters but carries a shape that is characteristic of many decay processes. Gamma is thus a widely used probability distribution function for which exponential and chi-square are special cases. In the chi-square case, κ describes the shape of the probability function and θ describes the scale (see Marland et al., 2010).

The gamma functions are represented in equation 5B-3 and illustrated in Figure 5-A-4 and figure 5-A-5. Whereas first-order decay assumes that the annual loss from the stock of products is a constant fraction of the amount of the stock, the chi-square function assumes that decay is a function of the time since production. First-order decay requires knowledge of only the half-life of the product, while the chi-square function requires estimates to represent both the time to maximum decay and a measure of the breadth of the distribution.

Equation 5B-3: Models of HWP Decay

$$\frac{dS}{dt} = \mathrm{J(t)} - \int_0^t P(t-\tau)J(\tau)d\tau$$

Where:

$$P(t,\kappa,\theta) = \frac{1}{\Gamma(\kappa)\theta^{\kappa}} t^{\kappa-1} e^{\frac{-t}{\theta}}$$

When κ = 1,

$$\frac{dS}{dt} = J(t) - \lambda S$$

First-order decay means the maximum amount of decay occurs in the first year, an unlikely circumstance for any product intended to serve a finite useful life. A chi-square probability distribution shows that the maximum rate of decays occurs at about the half-life. Figure 5B-1 shows the rate of decay for a first-order decay and for a chi-square decay for products with half-lives of 2.5, 12, 30, and 87.8 years, and figure 5B-1 illustrates the fraction remaining over time for the same probability descriptions of decay. The longer the service life of a class of products, the less likely that first-order decay can provide an accurate description. For long-lived products, the difference can be very important (Bates et al., 2017).

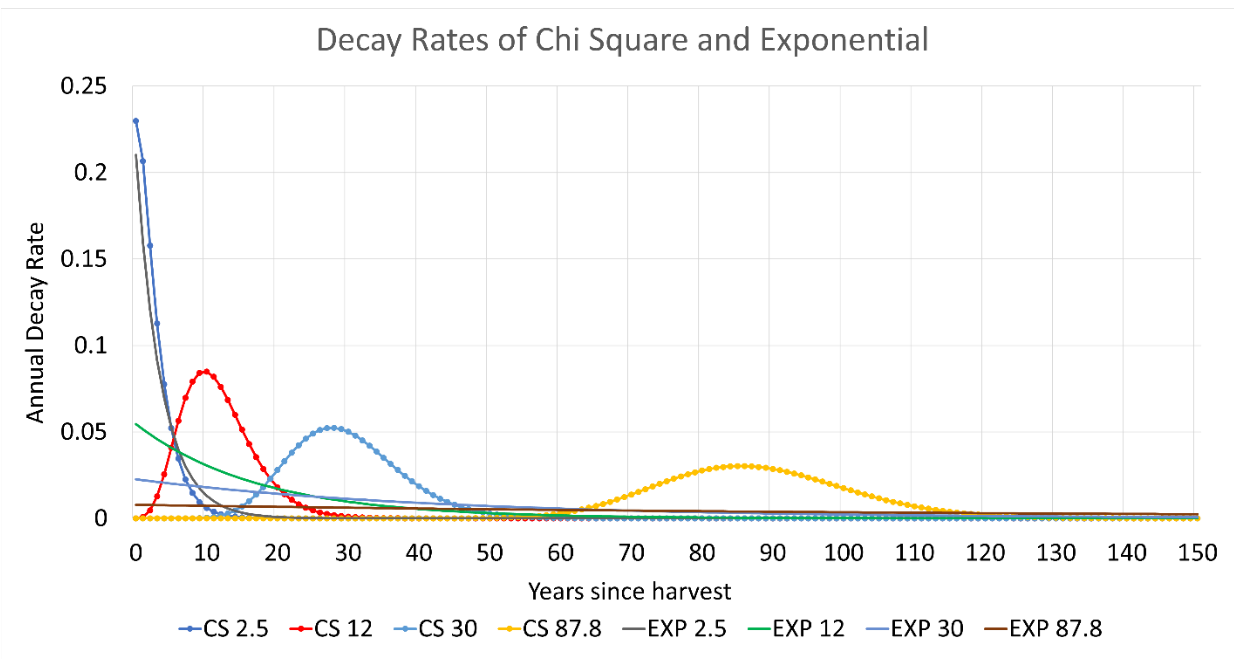


Figure 5B-1. Decay Rates for Chi-Square (CS) and Exponential (EXP) Probability Functions

Note that the exponential curves all start with their steepest decreases in earliest years and then flatten, whereas the chi-square curves peak as bell-shaped curves, with the highest rates of decrease stacked close to the actual half-lives. Chi-square curves have more delay, but more complete decay sooner than with the exponential curves.

Hazard function curves are a way to show how much of the original carbon remains through time. Figure 5B-2 shows the decimal decrease in remaining products in use when applying the exponential and gamma (chi-square) functions. These curves clearly show the differences between the two descriptions of "decay." Note that the curves sharing the same half-life cross very near their half-lives (e.g., CS-12 and E-12).

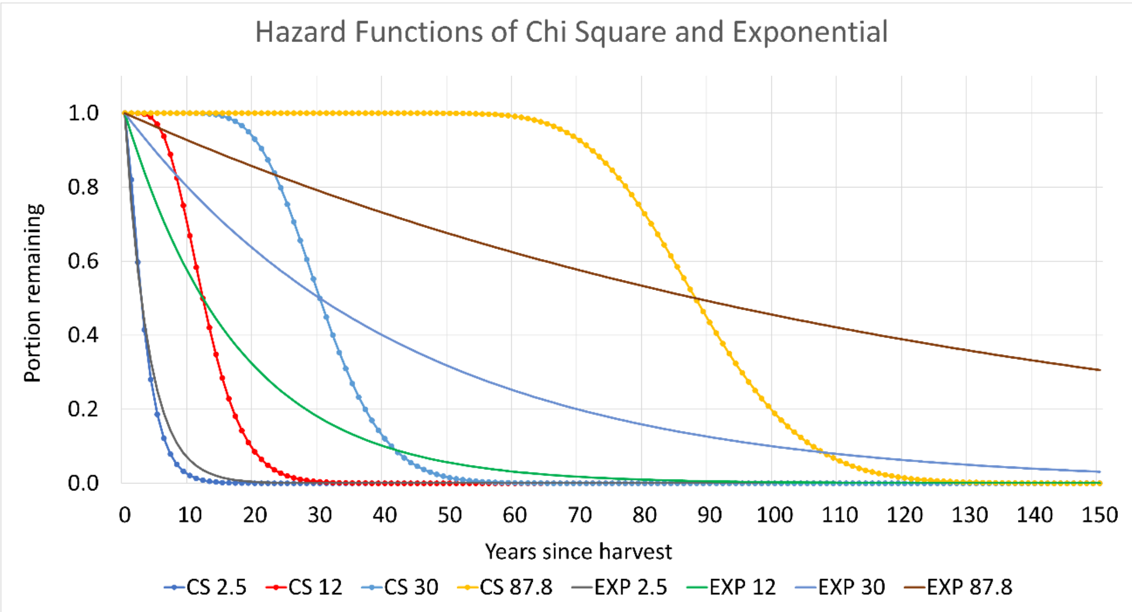


Figure 5B-2. Hazard Functions (Fraction Remaining Through Time) for Chi-Square (CS) and Exponential (E) Decay Curves

Because CO_2 emissions resulting from a given forest harvest that occurs during a discrete accounting year will occur over an extended number of years, a complete and accurate accounting of CO_2 emissions requires either a continued accounting and reporting of emissions in all subsequent years or an equitable protocol for anticipating all future emissions and accounting for the emissions during the initial accounting year that the forest was harvested. For accounting at the entity level, a few conventions have been widely adopted (e.g., those set by CARB, 2015).

End-of-Use Dispositions

Regardless of whether first-order or chi-square functions are used to portray the duration of product lives as products in use, once products are discarded, disposition ratios are relied on to shift products-in-use carbon into recycling, composting, burning with and without energy use, and landfills and dumps (SWDS).

Table 5B-7. Discard Percentages After Wood Products Have Completed Their Lives

Product Type	Disposition	2018 (%)
Paper	Burned	6
	Recycled	68
	Composted	0
	Landfills	26
	Dumps	0
Wood	Burned	16
	Recycled	17
	Composted	0
	Landfills	67
	Dumps	0

Source: Skog, 2020, personal communication, adapting U.S. EPA, 2020b. Skog (2008) summarized the understanding that some of the wood products in modern landfills "will stay there indefinitely with almost no decay." Recent U.S. EPA (2020a) estimates from 2018 indicate that 12 percent of solid wood carbon and 56 percent of paper carbon in landfills are subject to decay and indicated that solid wood and paper decaying in landfills had half-lives of 29 and 14.5 years, respectively (de Silva Alves et al., 2000; Freed and Mintz, 2003). Table 5B-9 summarizes the data used for calculations on carbon in landfills.

The combination of end-use lifespans, disposition, and decay rates in SWDS is also used to construct tables that show the percentage of wood remaining in products in use, the fraction remaining in SWDS, and (through subtracting from 1.0) the fraction emitted to the atmosphere by each year. These types of tables were originally constructed to derive a 100-year average for convenient representation of storage duration needed for financial compensation in carbon exchanges (e.g., Chicago, California). They will continue to be reported for the first 100 years, although carbon storage continues longer than 100 years for several primary products in several end uses (e.g., softwood lumber used in new home construction).

The harvest carbon calculator, described in section 5.2.2.1, uses these ratios and applies a set of assumptions about recycled material (a 2.5-year half-life for all paper products with unlimited recycling cycles). It then subjects 12 percent of solid wood and 56 percent of paper in landfills to decay.

Table 5B-8 shows the fractions of the carbon in wood products that is withheld from the atmosphere as a function of time for different products with different approximations of the half-life and for a chi-square version of the gamma function. The table also shows the average value over the commonly used 100 years (year 0 to year 99) and the value that would represent the average over 30 years, a time span that is typically meaningful for forest management decisions. Values out to 150 and 200 years are included to emphasize that the widely used 100-year average is a policy choice with no physical significance in terms of the system behavior. Table 5B-9 includes similar estimates of carbon remaining in SWDS.

Assumptions embedded in the results include a 5-percent discard when products are installed as end uses or used for the first time in year 1 (e.g., U.S EPA 2018b). Adhering to the disposition ratios in table 5B-8, 17 percent of the discarded material is recycled back into products in use. It is assumed that the half-lives, shown in table 5-8 (Skog, 2008), represent the year when half the wood installed in end-use products remains in these products.

Therefore, the Excel workbook applies a default chi-square distribution with these same half-lives to model alternative disposition rates into the future. Paper includes unlimited recycling (with a 0.68 rate with 0.7 efficiency), whereas solid wood products have a 0.17 rate with unlimited recycling. Paper, with a half-life in landfills of 14.5 years, is subject to faster landfill decay than solid wood, which has a landfill exponential decay with a half-life of 29 years. It is assumed that decay in landfills is exponential.

In general, it takes more time for products to transition to disposition than the fractions remaining in use generated by the exponential functions. However, the amount of carbon remaining at 100 years in solid wood products in the chi-square probabilities is roughly half of that from the exponential calculations. Whereas Hoover et al. (2014) chose to highlight the 100-year average results, this report presents the entire set of results in the calculator. However, the 100-year average can be a reasonable approximation of the avoided radiative forcing associated with carbon storage—a useful metric when 100-year GWPs are being used—so those results are also provided.

Table 5B-8. Total Carbon Fraction Remaining in End Uses: Chi-Square, Gamma Function

Time (Years Since Harvest)	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strand-board	NonStructural Panels	Other Industrial Products (Misc.)	Paper
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.950	0.948	0.950	0.950	0.950	0.950	0.950	0.943
2	0.948	0.935	0.949	0.950	0.950	0.950	0.950	0.864
3	0.945	0.910	0.946	0.949	0.950	0.949	0.948	0.787
4	0.939	0.875	0.942	0.946	0.949	0.946	0.941	0.716
5	0.931	0.835	0.936	0.941	0.947	0.941	0.927	0.651
6	0.921	0.794	0.929	0.932	0.943	0.932	0.900	0.591
7	0.908	0.753	0.919	0.919	0.938	0.919	0.862	0.537
8	0.893	0.713	0.908	0.902	0.931	0.902	0.812	0.487
9	0.876	0.676	0.896	0.882	0.924	0.882	0.753	0.442
10	0.859	0.642	0.883	0.861	0.915	0.861	0.688	0.402
11	0.841	0.610	0.870	0.839	0.906	0.839	0.621	0.365
12	0.824	0.582	0.857	0.817	0.897	0.817	0.555	0.331
13	0.807	0.557	0.845	0.796	0.888	0.796	0.491	0.301
14	0.791	0.534	0.833	0.776	0.879	0.776	0.433	0.273
15	0.776	0.514	0.821	0.757	0.871	0.757	0.380	0.248
16	0.762	0.496	0.809	0.739	0.863	0.739	0.333	0.225
17	0.748	0.480	0.797	0.722	0.855	0.722	0.292	0.204
18	0.734	0.465	0.785	0.706	0.847	0.706	0.257	0.185
19	0.720	0.450	0.773	0.689	0.839	0.689	0.226	0.168
20	0.706	0.436	0.759	0.673	0.831	0.673	0.200	0.153
21	0.692	0.422	0.746	0.656	0.822	0.656	0.177	0.139
22	0.678	0.408	0.731	0.638	0.814	0.638	0.157	0.126
23	0.663	0.393	0.716	0.619	0.805	0.619	0.139	0.114
24	0.649	0.378	0.701	0.599	0.797	0.599	0.124	0.104

Time (Years Since Harvest)	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strand-board	NonStructural Panels	Other Industrial Products (Misc.)	Paper
25	0.635	0.362	0.685	0.579	0.788	0.579	0.111	0.094
26	0.621	0.347	0.670	0.558	0.780	0.558	0.098	0.086
27	0.607	0.330	0.654	0.537	0.772	0.537	0.088	0.078
28	0.594	0.314	0.639	0.516	0.764	0.516	0.078	0.071
29	0.582	0.298	0.625	0.495	0.757	0.495	0.069	0.064
30	0.570	0.282	0.611	0.475	0.750	0.475	0.062	0.058
31	0.559	0.267	0.598	0.455	0.744	0.455	0.055	0.053
32	0.549	0.252	0.586	0.436	0.738	0.436	0.049	0.048
33	0.540	0.238	0.575	0.418	0.733	0.418	0.043	0.044
34	0.532	0.224	0.565	0.401	0.729	0.401	0.038	0.040
35	0.525	0.212	0.556	0.386	0.724	0.386	0.034	0.036
36	0.518	0.200	0.548	0.371	0.721	0.371	0.030	0.033
37	0.512	0.189	0.540	0.358	0.717	0.358	0.027	0.030
38	0.507	0.179	0.533	0.346	0.714	0.346	0.024	0.027
39	0.502	0.170	0.527	0.335	0.711	0.335	0.021	0.024
40	0.497	0.161	0.522	0.325	0.709	0.325	0.019	0.022
41	0.493	0.154	0.517	0.316	0.706	0.316	0.017	0.020
42	0.490	0.147	0.512	0.308	0.704	0.308	0.015	0.018
43	0.486	0.141	0.508	0.301	0.702	0.301	0.013	0.017
44	0.483	0.135	0.504	0.294	0.699	0.294	0.012	0.015
45	0.480	0.130	0.501	0.288	0.697	0.288	0.010	0.014
46	0.477	0.126	0.497	0.282	0.695	0.282	0.009	0.012
47	0.474	0.122	0.494	0.277	0.693	0.277	0.008	0.011
48	0.471	0.118	0.490	0.272	0.690	0.272	0.007	0.010
49	0.468	0.115	0.487	0.267	0.688	0.267	0.006	0.009
50	0.465	0.111	0.484	0.263	0.685	0.263	0.006	0.008
55	0.450	0.098	0.466	0.243	0.671	0.243	0.003	0.005
60	0.432	0.087	0.446	0.224	0.653	0.224	0.002	0.003
65	0.410	0.077	0.422	0.205	0.628	0.205	0.001	0.002
70	0.383	0.067	0.393	0.185	0.594	0.185	0.001	0.001
75	0.349	0.058	0.357	0.165	0.546	0.165	0.000	0.001
80	0.307	0.048	0.314	0.143	0.484	0.143	0.000	0.000
85	0.261	0.040	0.267	0.121	0.411	0.121	0.000	0.000
90	0.214	0.032	0.219	0.099	0.337	0.099	0.000	0.000
95	0.170	0.025	0.176	0.080	0.269	0.080	0.000	0.000
100	0.134	0.019	0.140	0.063	0.213	0.063	0.000	0.000
150	0.033	0.001	0.035	0.010	0.074	0.010	0.000	0.000
200	0.008	0.000	0.009	0.002	0.020	0.002	0.000	0.000

Time (Years Since Harvest)	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Hardwood Plywood	Oriented Strand-board	NonStructural Panels	Other Industrial Products (Misc.)	Paper
30-year average	0.787	0.582	0.819	0.765	0.872	0.765	0.485	0.358
100-year average	0.503	0.240	0.523	0.381	0.659	0.381	0.151	0.114

Notes:

- It is assumed 12 percent of solid wood going to landfill decays and 88 percent does not (landfill permanent). Solid wood in landfills decays exponentially with a half-life of 29 years.
- It is assumed 56 percent of paper going to landfills decays and 44 percent does not (landfill permanent). Paper in landfills decays exponentially with a half-life of 14.5 years.
- Solve for κ in the chi-square distributions by setting the median equal to the half-life (equation 5B-3).
- Sixty-seven percent of disposed solid wood products go to landfills; 26 percent of disposed paper products go to landfills.
- Seventeen percent of disposed solid wood is recycled, including the 5-percent loss during installation in year 1.
- Sixty-eight percent of disposed paper products are recycled, with no installation loss at year 1.
- Landfill decay is assumed to be exponential.
- Hardwood plywood is pooled with nonstructural panels.
- Values indicate amounts at the beginning of the year rather than the middle or end of the year.
- This table assume a 5-percent loss of products at installation between year 0 and year 1.

Table 5B-9. Total Carbon Fraction Remaining in Landfills (SWDS): Chi-Square, Gamma Function

Time (Years Since Harvest)	Soft-wood Lumber	Hard-wood Lumber	Softwood Plywood	Hard-wood Plywood	Oriented Strand-board	Non-Structural Panels	Other Industrial Products (Misc.)	Paper
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.040	0.042	0.040	0.040	0.040	0.040	0.040	0.046
2	0.042	0.052	0.041	0.040	0.040	0.040	0.040	0.108
3	0.044	0.072	0.043	0.041	0.040	0.041	0.042	0.168
4	0.049	0.100	0.046	0.043	0.041	0.043	0.047	0.221
5	0.055	0.132	0.051	0.047	0.043	0.047	0.059	0.268
6	0.063	0.165	0.057	0.055	0.045	0.055	0.080	0.310
7	0.073	0.198	0.064	0.065	0.049	0.065	0.110	0.346
8	0.085	0.229	0.073	0.078	0.054	0.078	0.150	0.377
9	0.098	0.259	0.083	0.094	0.061	0.094	0.198	0.404
10	0.112	0.286	0.093	0.111	0.067	0.111	0.249	0.427
11	0.126	0.310	0.103	0.128	0.075	0.128	0.303	0.447
12	0.140	0.332	0.113	0.146	0.082	0.146	0.356	0.464
13	0.153	0.352	0.123	0.162	0.089	0.162	0.406	0.478
14	0.166	0.369	0.133	0.178	0.096	0.178	0.452	0.490
15	0.177	0.384	0.142	0.193	0.102	0.193	0.494	0.499

Time (Years Since Harvest)	Soft-wood Lumber	Hard-wood Lumber	Softwood Plywood	Hard-wood Plywood	Oriented Strand-board	Non-Structural Panels	Other Industrial Products (Misc.)	Paper
16	0.189	0.398	0.151	0.207	0.108	0.207	0.530	0.507
17	0.200	0.410	0.160	0.220	0.115	0.220	0.562	0.513
18	0.210	0.422	0.170	0.233	0.121	0.233	0.589	0.517
19	0.221	0.432	0.179	0.245	0.127	0.245	0.612	0.520
20	0.232	0.443	0.189	0.258	0.133	0.258	0.632	0.522
21	0.242	0.453	0.200	0.271	0.140	0.271	0.649	0.523
22	0.253	0.464	0.211	0.285	0.146	0.285	0.664	0.523
23	0.264	0.474	0.223	0.300	0.153	0.300	0.676	0.523
24	0.275	0.486	0.235	0.315	0.159	0.315	0.687	0.522
25	0.286	0.497	0.247	0.330	0.166	0.330	0.696	0.520
26	0.297	0.509	0.259	0.346	0.172	0.346	0.705	0.518
27	0.307	0.521	0.271	0.363	0.178	0.363	0.712	0.515
28	0.317	0.533	0.282	0.379	0.184	0.379	0.718	0.512
29	0.326	0.545	0.293	0.395	0.189	0.395	0.724	0.509
30	0.335	0.556	0.304	0.411	0.194	0.411	0.728	0.505
31	0.343	0.568	0.313	0.426	0.199	0.426	0.732	0.502
32	0.350	0.579	0.322	0.440	0.203	0.440	0.736	0.498
33	0.357	0.589	0.331	0.454	0.207	0.454	0.739	0.494
34	0.363	0.599	0.338	0.466	0.210	0.466	0.741	0.490
35	0.368	0.608	0.345	0.478	0.213	0.478	0.743	0.486
36	0.373	0.616	0.351	0.488	0.216	0.488	0.745	0.482
37	0.377	0.624	0.356	0.498	0.218	0.498	0.747	0.478
38	0.381	0.631	0.361	0.507	0.220	0.507	0.748	0.474
39	0.384	0.637	0.365	0.515	0.222	0.515	0.749	0.470
40	0.387	0.643	0.369	0.522	0.224	0.522	0.749	0.466
41	0.389	0.648	0.372	0.528	0.226	0.528	0.750	0.462
42	0.392	0.652	0.375	0.533	0.227	0.533	0.750	0.458
43	0.394	0.656	0.378	0.538	0.228	0.538	0.750	0.454
44	0.396	0.659	0.380	0.543	0.230	0.543	0.750	0.451
45	0.397	0.662	0.383	0.547	0.231	0.547	0.750	0.447
46	0.399	0.665	0.385	0.550	0.233	0.550	0.750	0.444
47	0.401	0.667	0.387	0.554	0.234	0.554	0.750	0.440
48	0.402	0.669	0.389	0.557	0.236	0.557	0.749	0.437
49	0.404	0.671	0.391	0.560	0.237	0.560	0.749	0.434
50	0.406	0.672	0.393	0.562	0.239	0.562	0.748	0.431
55	0.415	0.678	0.404	0.574	0.249	0.574	0.746	0.416
60	0.427	0.683	0.417	0.585	0.262	0.585	0.743	0.404
65	0.442	0.687	0.434	0.596	0.280	0.596	0.739	0.395
70	0.461	0.691	0.455	0.609	0.305	0.609	0.736	0.387

Time (Years Since Harvest)	Soft-wood Lumber	Hard-wood Lumber	Softwood Plywood	Hard-wood Plywood	Oriented Strand-board	Non-Structural Panels	Other Industrial Products (Misc.)	Paper
75	0.486	0.696	0.481	0.622	0.342	0.622	0.734	0.380
80	0.517	0.700	0.513	0.636	0.390	0.636	0.731	0.375
85	0.551	0.705	0.548	0.651	0.445	0.651	0.729	0.371
90	0.586	0.708	0.583	0.665	0.502	0.665	0.727	0.368
95	0.618	0.712	0.614	0.678	0.553	0.678	0.725	0.365
100	0.644	0.714	0.640	0.688	0.594	0.688	0.723	0.363
150	0.700	0.715	0.699	0.713	0.674	0.713	0.714	0.356
200	0.710	0.712	0.709	0.712	0.704	0.712	0.711	0.355
30-year average	0.168	0.329	0.143	0.186	0.100	0.186	0.406	0.410
100-year average	0.376	0.572	0.362	0.468	0.260	0.468	0.638	0.410

Notes:

- It is assumed 12 percent of solid wood going to landfill decays and 88 percent does not (landfill permanent). Solid wood in landfills decays exponentially with a half-life of 29 years.
- It is assumed 56 percent of paper going to landfills decays and 44 percent does not (landfill permanent). Paper in landfills decays exponentially with a half-life of 14.5 years. Solve for κ in the chi-square distributions by setting the median equal to the half-life (equation 5B-3).
- Sixty-seven percent of disposed solid wood products go to landfills; 26 percent of disposed paper products go to landfills.
- Seventeen percent of disposed solid wood is recycled, including the 5-percent loss during installation in year 1.
- Sixty-eight percent of disposed paper products are recycled, with no installation loss at year 1.
- Landfill decay is assumed to be exponential.
- Hardwood plywood is pooled with nonstructural panels.
- Values indicate amounts at the beginning of the year rather than the middle or end of the year.
- This table assume a 5-percent loss of products at installation between year 0 and year 1.

Table 5B-8 and table 5B-9 represent substantial development in this field and appear to more realistically represent the lifespans for durable wood products. There is ongoing discussion of whether paper products are better represented with an exponential function or a chi-square probability function. This discussion will be explored further in ongoing work, and options are provided to use in the harvest carbon calculator.

Table 5B-10 provides the converted GHG emissions (i.e., ton CO_2-eq emission/ton CO_2-eq) contained in the HWP. This version of the table using CO_2-eq for the product amounts (numerator) makes it easy to use results from the harvest carbon calculator in the substitution calculations.

Emission factors are also divided into the three life cycle stages as displayed in the table.

Table 5B-10. LCA Quantified GHG Emission Factors for Cradle-to-Gate Manufacturing of HWPs

Type	Cultivation and Harvest	Transportation	Manufacturing	Total
	Metric Tons CO_2-eq/Tons CO_2-eq Contained in the HWP Produceda			
Softwood lumber	0.015	0.012	0.061	0.088
Hardwood lumber	0.024	0.028	0.096	0.149
Plywood	0.077	0.012	0.173	0.263
Oriented strandboard	0.071	0.006	0.136	0.213
Non-structural panels	0.205	0.006	0.241	0.452
Other industrial products	0.055	0.037	0.056	0.148

[a] Values rounded to the thousandths place.

Calculator Demonstrations

The following example walks through the calculations performed by the growing stock calculator and the harvested wood carbon calculator, both embedded within the Excel workbook. Importantly, the models that underly some of the calculations in the demonstrations below include more decimals than are shown in the text, so slight discrepancies in results may be a function of rounding. As a brief navigation reminder:

- Read the information on the "Instructions and Context" tab before proceeding.
- Enter information on the "User Data Entry" tab.
- Depending on the forest management treatment and the region selected, real-time estimates for ecosystem carbon may or may not be available on the "User Data Entry" tab. The year-0 and year-100 results for HWP are part of the "Forest Management & HWP Results" tab.
- As stated in section 5.1.6, users can use default harvest volumes or provide their own to estimate the amount of ecosystem carbon that is taken off site as a result of harvest under the "Basic projection under fm, with harvest," "Harvest," or "Extended rotation" forest management activities available under the Level 1 approach. Consider that these two options are available when reviewing the calculator demonstrations:
    - **Advanced option.** Manually enter known harvest volumes or weights from logging/mill receipts or consultant reports, wood types (hardwood, softwood, unknown) and product types (sawlogs, pulpwood, fuelwood, unknown) as totals or per-acre values, as well as percentage of total growing stock harvested.
    - **Default data option.** Use default FIA data on regional growing stock volumes (cubic foot net volume per acre based on user-selected parameters around region/forest type group/stand age class/stand origin) for medium- and large-diameter stands to estimate harvest amounts.

In the following calculator examples, assume the user has the following criteria:

- The natural, spruce/fir, 1-square-mile forest stand is located in Maine and is about 21 to 40 years old. See figure 5-4 for a map of how the geographic regions are delineated.
- The scenario involves plans to harvest in 45 years.

- The expected harvest is softwood sawlogs; the user also plans to cut fuelwood in addition to industrial roundwood.

This criterion translates to the following selections on the "User Data Entry" tab.

- Basic inputs (blue section on the tab):
  - Type of forest management treatment to be applied: "Basic projection under fm, with harvest"
  - Area subject to management activity: 640 acres (1 square mile)
  - U.S. region: Northeast region
  - Forest type group: spruce/fir forest type group, natural stand origin, 21- to 40-year age class
- Silviculture and harvesting inputs (green and brown sections on the tab)
  - Number of years from now that you plan to harvest: 45
  - Percent of the area subject to management activity that will be harvested: 100 percent (the default)

Growing Stock Calculator

Default Data Option

- The user has limited knowledge on the harvest volume, but based on conversations with a local logger, the user expects to cut softwood sawlogs and plans to cut fuelwood in addition to industrial roundwood (sawlogs and pulpwood) for personal fuelwood use.
- This translates to the following Excel workbook data entry questions and example user selection on the "User Data Entry" tab:
  - Do you know what your harvest volume is? No
  - Main wood type of eventual products: Softwood
  - What is the main log type that will be produced from the trees removed? Sawlog
  - Should the tool apply default fuelwood values that are generated from sawlog and pulpwood production? Yes
- In the subsequent growing stock calculator analysis, the calculator:
  1. Begins with a FIADB CFNETVOL lookup for harvest volume. The age of the stand is the existing age stand plus the years until harvest. Since the midpoint of the current age class of 21–40 is 30, and the harvest is planned at 45 years, the age used by the lookup is 76 years, which falls in the 61–80 age class. The result is 15.28 CCF per acre, multiplied by all 640 acres, resulting in 9,780.9 CCF.
  2. Multiplies the result from step 1 by the softwood sawlog ratio of roundwood growing stock to volume that is removed as roundwood (0.991 from Smith et al., 2006, table 5). The result is 9,693 CCF.
  3. Multiplies the result from step 2 by the fraction of growing stock volume that is removed as roundwood, for softwood sawlogs in this region (0.948 from Smith et al., 2006, table 5) resulting in 9,189 CCF of softwood sawlogs.
  4. To expand back to the full growing stock and derive the fuelwood, the calculator divides the result from step 3 by the softwood sawlog ratio of roundwood to growing stock volume that is roundwood from Smith et al. (2006), table 5 (0.991), then multiplies by

the Northeast softwood sawlog ratio of fuelwood to growing stock volume that is roundwood (0.136): $\frac{9{,}189 \text{ CCF}}{0.991} \times 0.136 = 1{,}261 \text{ CCF}$.

So, in this example, the growing stock calculator estimates that the harvest in 45 years from 100 percent of the 640-acre stand will include 9,189 CCF softwood sawlogs and 1,261 CCF of softwood fuelwood. This information is then automatically moved into the harvest carbon calculator.

When the forest type group is unknown, the calculator uses an overall average of forest types by region. If the landowner does not know the forest type or wood type (i.e., softwood or hardwood) or the type of timber product (i.e., sawlog, pulpwood, or fuelwood), the calculator uses information from Smith et al. (2006) table 4 (fraction of growing stock volume that is softwood, fraction of growing stock volume that is sawtimber size) to allocate wood across a range of classes (softwood and hardwood, as well as sawlogs and pulpwood).

Advanced Option

This option may be preferred by users who have more advanced forestry operations and data or those who have had exchanges with an extension forester. It is only available for the "Basic projection under forest management (fm)" and "Basic projection under fm, with harvest" forest management activities in the Excel workbook.

This translates to the following Excel workbook data entry questions and example user selection:

- Do you know what your harvest volume is? Yes
- What is the amount you harvested or plan to harvest? (under product type 1): 7.5 MBF/acre
- What is the MAIN wood type of eventual products? Softwood
- What is the MAIN log type that will be produced from the trees removed? Sawlog
- Should the tool apply default fuelwood values that are generated from sawlog and pulpwood production? Yes

In the subsequent growing stock calculator analysis, the calculator:

1. Multiplies 640 acres $\times$ 7.5 MBF/acre = 4,800 MBF.
2. To expand back to the full growing stock and derive the fuelwood, the calculator divides the result from step 1 by the softwood sawlog ratio of roundwood to growing stock volume that is roundwood from Smith et al. (2006), table 4 (0.991).
3. Multiplies by the Northeast softwood sawlog ratio of fuelwood to growing stock volume that is roundwood (0.136): $\frac{4{,}800 \text{ MBF}}{0.991} \times 0.136 = 658.7 \text{ MBF}$.

So, in this example, the growing stock calculator estimates that the harvest in 45 years from 100 percent of the 640-acre stand will include 4,800 MBF softwood sawlogs and 658.7 MBF softwood fuelwood. This information is then automatically moved into the harvest carbon calculator (see the next example).

Harvest Carbon Calculator

In the advanced option example described above, the harvest amount is known. There are 4,800 MBF of Northeast spruce fir softwood sawlog volume and 658.7 MBF of Northeast spruce/fir fuelwood.

1. The harvest carbon calculator converts these inputs to an equivalent CCF, then chooses the highest value for each row. This prevents the user from double counting if they accidentally enter the same harvest in multiple units. This step uses one or two of four conversions depending on the provided units:
   - An MBF-to-CCF conversion, using a rate of 2.01 (based on a 4.97 ratio of board feet to cubic feet ratio, as well as the conversion factors of 1,000 board feet per MBF and 100 cubic feet per CCF).
   - A dry-tons-to-CCF conversion using the correct basic specific gravities, which allows conversion of green volumes to oven dry (zero moisture content) weight. In this case, the relevant specific gravity is softwood spruce fir's: 0.353, from Smith et al. (2006), table 4.
   - A green-tons-to-CCF conversion. This is the same as the dry-tons-to-CCF conversion, except that it also includes the dry log weight relative to wet log weight for softwoods (0.49), assuming an average moisture content of 106 percent for softwood (Forest Products Laboratory, 2010, table 4.1).
   - A cord-to-green-ton conversion of 2.15 tons per cord (all western, green tons without bark per cord; Winn et al., 2020, table 30).

   In this example, the CCF values are:

   $4{,}800 \text{ MBF} \times \frac{2.01 \text{ CCF}}{\text{MBF}} = 9{,}657.9 \text{ CCF}$ Northeast spruce fir softwood sawlog

   $658.7 \text{ MBF} \times \frac{2.01 \text{ CCF}}{\text{MBF}} = 1{,}325.4 \text{ CCF}$ Northeast spruce fir fuelwood

   The calculator then completes two sequential checks using two national biomass limits (Johnson, 2001) to ensure that no more than 66 percent of total site biomass is being harvested as industrial roundwood and no more than 78 percent of site biomass is being harvested as roundwood (sawlogs, pulpwood, and fuelwood). In both cases, if the amount being harvested is greater than the limit, the limit is divided by the percentage harvest to derive an adjustment factor, which is applied to all sawlogs and pulpwood for the first limit, followed by recalculation of fuelwood (when that is selected as harvested), and applied to sawlogs, pulpwood, and fuelwood for the second limit. These adjustments are made to the inputs for the harvest carbon calculator. Bark adjustments are captured in the harvest carbon calculator, working with the new limited amounts, and are linked to the potential substitution calculator.
2. The timber products are broken into primary products using table D6 from Smith et al. (2006) (table 5B-4). In this case, the calculator multiplies the sawlog volume by the following allocations. (There is no pulpwood in this example, but if there were, it would be allocated to a different set of ratios.)

   9,657.9 CCF × 0.391 (softwood lumber) = 3,776.3 CCF

   9,657.9 CCF × 0.000 (hardwood lumber) = 0 CCF

   9,657.9 CCF × 0.004 (softwood plywood) = 38.6 CCF

   9,657.9 CCF × 0.000 (hardwood plywood) = 0 CCF

   9,657.9 CCF × 0.000 (oriented strandboard) = 0 CCF

   9,657.9 CCF × 0.020 (nonstructural panel) = 193.2 CCF

   9,657.9 CCF × 0.083 (other industrial products) = 801.6 CCF

   9,657.9 CCF × 0.072 (wood pulp) = 695.4 CCF

9,657.9 CCF × 0.431 (fuel and other emissions) = 4,162.6 CCF

Note that these ratios should total 1.000, but they sum to 1.001 due to rounding.

3. The calculator then converts the CCFs from step 2 into carbon mass by multiplying each CCF by the correct basic specific gravities, which allows conversion of green volumes to oven dry (zero moisture content) weight:

$$\left(\frac{0.353 \times \frac{62.4\ \text{lb}}{\text{ft}^3}}{2{,}000\ \frac{\text{lb}}{\text{ton}}}\right) \times \frac{0.907185\ \text{metric ton}}{\text{ton}} \times \frac{100\ \text{ft}^3}{\text{CCF}} \times 0.5 = 0.4996\ \frac{\text{Mg C}}{\text{CCF}}$$

where 0.353 is the ratio of softwood spruce fir from Smith et al. (2006) table 4, and 0.5 is the carbon weight relative to dry wood.

3,776.2 CCF × 0.4996 (softwood lumber) = 1,886.5 Mg C

38.6 CCF × 0.4996 (softwood plywood) = 19.3 Mg C

193.2 CCF × 0.4996 (nonstructural panel) = 96.5 Mg C

801.6 CCF × 0.4996 (other industrial products) = 400.5 Mg C

695.4 CCF × 0.4996 (wood pulp) = 347.4 Mg C

therefore, = 2,750.1 Mg C (all products)

4,162.6 CCF × 0.4996 (fuel and other carbon) = 2,079.5 Mg C

It also calculates estimates from the fuelwood line:

1,325.4 CCF × 0.4996 (fuelwood) = 662.1 Mg C

The Fuel and other emissions are split into emissions with and without energy capture using Smith et al. (2006) table 7 with the tool weighting the capture ratios by timber product volumes. The results are converted to metric tons CO_2-eq and added to other emissions. Mg C results are shown in the emissions results in the harvest carbon calculator and they are converted into t CO_2-eq for the "Forest Mgmt & HWP Results" tab.

2,079.5 Mg × 0.5582 = 1,160.8 Mg Fuel and other emissions with energy capture

2,079.5 Mg × (1- 0.5582) = 918.7 Mg Fuel and other emissions without energy capture

4. The calculator multiplies the carbon mass for all products, fuel and other carbon, and fuelwood calculated in step 3 by table 5B-3's ratios of carbon in bark to carbon in wood by region and timber product type (in this case, 0.182 for the sawlog-derived products and 0.185 for fuelwood (table does not provide fuelwood-specific ratios—pulpwood was selected)) to estimate the total bark carbon equivalent. To calculate the bark carbon emitted, the calculated bark carbon equivalent is multiplied by energy capture (0.5582) and without energy capture (1 – 0.5582), based coefficients and the formula provided in Smith et al. (2006) table D7 and its footnotes. Fuelwood and its bark are all assumed to be emitted with energy capture (1.0).

$(2{,}750.1 + 2{,}079.5\ \text{Mg}) \times 0.182 \times 0.5582 = 490.7$ Mg equivalent sawlog bark carbon emissions with energy capture

$(2{,}750.1 + 2{,}079.5\ \text{Mg}) \times 0.182 \times (1 - 0.5582) = 388.4$ Mg equivalent sawlog bark carbon emissions without energy capture

$662.1\ \text{Mg} \times 0.185 \times 1.0 = 121.2$ Mg equivalent fuelwood bark carbon emissions with energy capture

Therefore,

$$\text{Total bark with energy capture} = (490.7 + 388.4 + 121.2 \text{ Mg C}) \times \frac{44 \text{ CO}_2\text{-eq}}{12 \text{ C}}$$
$$= 1{,}000.3 \text{ Mg or metric tons CO}_2\text{-eq}$$

5. The calculator multiplies the results in step 4 by the fractions remaining in end uses and fractions remaining in SWDS every year for the first 50 years and every 5 years from 55 to 100 years, as shown in table 5B-8 and table 5B-9. Note that all solid wood (not wood pulp/paper) products are reduced by 5 percent when end uses are installed between year 0 and year 1; this 5 percent is immediately disposed of at year 1. This next block of columns in this demonstration shows estimates of carbon from the sawlog line. For example, at year 10, 0.859 of softwood lumber and 0.883 of softwood plywood remain in end uses. Also at year 10, 0.112 of softwood lumber and 0.093 of softwood plywood remain stored in landfills. These remaining fractions are multiplied by the total amount produced in year 0 to obtain the total carbon amounts remaining in end uses and landfills. For example:

    Remaining in end uses at year 10:

    1,886.5 Mg C × 0859 (softwood lumber) = 1,620.5 Mg C

    19.3 Mg C × 0.883 (softwood plywood) = 17.0 Mg C

    Remaining in SWDS:

    1,886.5 Mg C × 0.112 (softwood lumber) = 211.7 Mg C

    19.3 Mg C × 0.093 (softwood plywood) = 1.8 Mg C

    To calculate the estimated carbon remaining in products in use and SWDS with conventional exponential functions, manually replace fractions remaining from table 5B-8 with those in table 5B-5 and fractions in table 5B-9 with those in table 5B-6.

    Remaining in end uses at year 10:

    1,886.5 Mg C × 0.700 (softwood lumber) = 1,319.7 Mg C

    19.3 Mg C × 0.722 (softwood plywood) = 13.9 Mg C

    Remaining in landfills (SWDS) at year 10:

    1,886.5 Mg C × 0.239 (softwood lumber) = 450.4Mg C

    19.3 Mg C × 0.221 (softwood plywood) = 4.3 Mg C

    In both cases, results across all primary product types are summed for each year and reported in the harvest carbon calculator, columns B, C and D as carbon stored in products in use, SWDS, and combined as Mg C or CO_2-eq.

    For example, using the chi-square lifespans, at year 10, products in use are estimated at 2,135.8 Mg C, SWDS at 472.5 Mg C, and combined HWPs stored at 2,608.3 Mg C. In the same row, in Columns F and G, note 95 percent of end-use carbon, but 47 percent of all log carbon (underbark) remained stored. During year 10, emissions with energy capture from the wood itself are estimated at 40 metric tons CO_2-eq, and emissions without energy capture are estimated at 29 metric tons CO_2-eq. By year 10, a total of 10,573 metric tons CO_2-eq is emitted (53 percent of total carbon in log removals (underbark)).

    Alternatively, in the results table on the “Harvest Carbon Calculator” tab in columns B, C and D, at row 80, for exponential end-use lifespans, at year 10, products in use are estimated at 1,703.2 Mg C, SWDS at 811.7 Mg C, and combined HWPs stored at 2,514.9 Mg C. This estimation is 91 percent of end-use carbon, but 46 percent of all log carbon (underbark). During year 10, emissions with energy capture are estimated at 437 metric tons CO_2-eq, and emissions without energy capture are estimated at 29 metric tons CO_2-eq. There is a total of

10,915 metric tons CO_2-eq emitted by year 10 (47 percent of total carbon in log removals (underbark)).

For this example, the ecosystem carbon stocks at year 45 are 175,980; subtracting that number from the year 0 stocks of 73,247 yields a cumulative ecosystem sequestration estimate of –102,733 tons CO_2-eq. On the "User Data Entry" tab, see the "Detailed Ecosystem Carbon Scenario Projection" part of the display to the right of the user selection for these values.

On the "Forest Mgmt & HWP Results" tab, the cumulative ecosystem sequestration value forms the beginning of the overall forest sector flux estimate. This tab's green section describes the resulting ecosystem pool:

A. Overall ecosystem carbon estimate before harvest: 175,980 metric tons CO_2-eq. This lines up with the year 45 total ecosystem carbon estimate from the "User Data Entry" tab.
B. CO_2-eq removed due to carbon stocks in sawlogs harvested: 17,709 metric tons CO_2-eq—that is, the amount of harvest reported in its CO_2-eq that was removed (recall in this example that 7.5 MBF/acre was removed) sawlogs.
C. CO_2-eq removed due to carbon stocks in pulpwood harvest: in this example, no pulpwood was removed.
D. But fuelwood was removed, as indicated by the 2,428 metric tons CO_2-eq on that row.
E. The result of the bark calculations indicates that 3,667 metric tons CO_2-eq was removed as bark and emitted from the ecosystem (in year 0, it is assumed).
F. Logging residue estimates from Smith et al. (2006), taken from Johnson (2001), were used to estimate the logging residue ecosystem emissions associated with the harvest: 5,289 metric tons CO_2-eq.
G. Remaining medium and large growing stock volume: zero, in this case, because extended harvest assumes 100 percent cut. (This number would show remaining wood under a harvest treatment with less than 100 percent removal.)
H. Remaining other aboveground carbon in the ecosystem after harvest: 146,887 metric tons CO_2-eq.

For the HWP section (the brown section on the tab) results are shown for year 0 (which in this case is 45 years from now, because that is when harvest is planned) and year 100, which corresponds to 145 years from now.

I. Amounts of carbon stored each of these years in harvested wood products in use: 10,084 and 959 metric tons CO_2-eq, respectively, for years 0 and 100.
J. Amounts stored in SWDS for each of the years: 0 and 6,265 metric tons CO_2-eq, respectively.
K. Emissions without energy capture: 3,369 and 4,718 metric tons CO_2-eq, respectively.
L. Emissions with energy capture: 6,684 and 8,194 metric tons CO_2-eq, respectively.

The total biogenic carbon stored from harvest (the sum of the storage subpools) is 10,084 metric tons CO_2-eq in use and 0 metric tons CO_2-eq in SWDS at year 0.

The final yellow cells on the tab show the total forest sector flux resulting from the management action in year 0; in other words, the net ecosystem exchange plus harvest minus change in HWP stock. This is the estimated stock change (flux) in forest sector carbon; it equals net ecosystem exchange (negative sequestration or zero sequestration) plus bark and logging residues emitted, plus harvested sawlogs, pulpwood, and fuelwood (annual stock change in harvested wood products in use and SWDS—year 0). The difference between total harvest and change in HWP equals HWP emissions with and without energy capture combined, so HWP emissions are captured indirectly in the following calculations.

Net ecosystem exchange is:

$$-102{,}733 + 3{,}667\ (\#E) + 5{,}289 \text{ metric tons } CO_2\text{-eq } (\#F) = -93{,}777 \text{ metric tons } CO_2\text{-eq}$$

Harvest is:

$$17{,}709\ (\#B) + 0 \text{ metric tons } CO_2\text{-eq } (\#C) + 2{,}428 \text{ metric tons } CO_2\text{-eq } (\#D) = 20{,}136 \text{ metric tons } CO_2\text{-eq}$$

Change in HWP stock is:

$$10{,}084\ (\#I) + 0 \text{ metric tons } CO_2\text{-eq } (\#J) = 10{,}084 \text{ metric tons } CO_2\text{-eq}$$

Therefore,

$$\text{Net Forest Sector Flux} = \text{Net Ecosystem Exchange} + \text{Harvest} - \text{Change in HWP Stock}$$

$$-93{,}777 + 20{,}136 - 10{,}084 \text{ metric tons } CO_2\text{-eq} = -83{,}724 \text{ metric tons } CO_2\text{-eq}$$

In other words, dependent on system boundaries across time this management action of waiting 45 years and then harvesting resulted in net forest sector flux of negative 83,724 metric tons CO_2-eq, meaning more carbon was sequestered than emitted under this scenario. No estimate is provided beyond the single harvest evaluation time (45 years from now or year 0), as there is not sufficient research to reliably estimate beyond that point. To toggle between the chi-square and exponential lifespan decay rates, use the down arrow that appears when cell B19 of the "Forest Mgmt & HWP Results" tab is selected. Switching between the options only affects the 100-year estimates in column D.

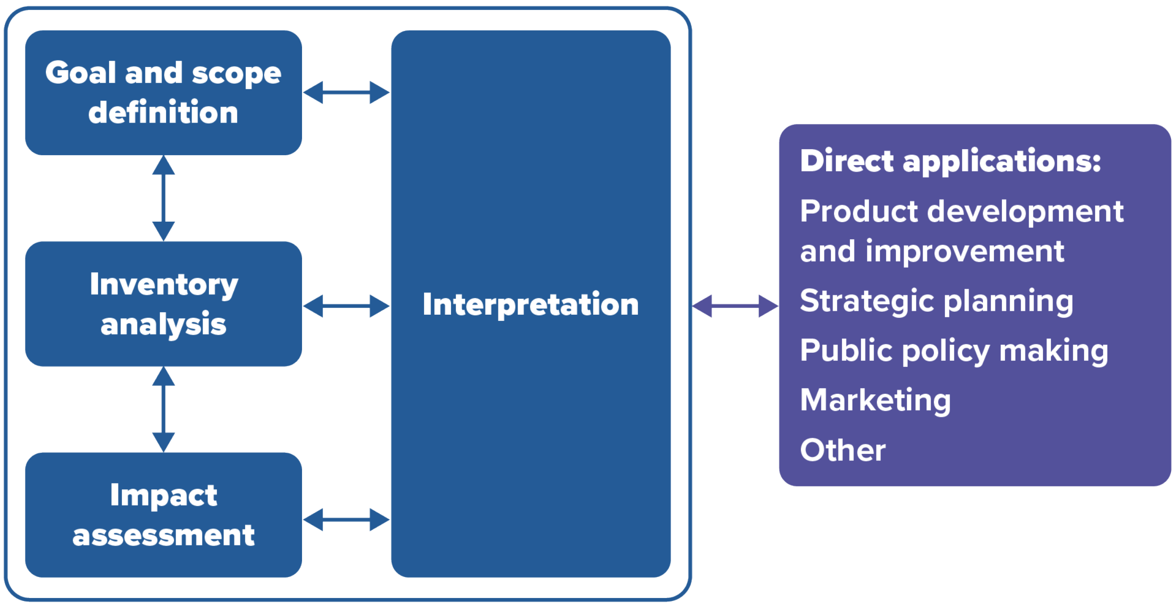
5-B.2.3 LCA Method Overview and Demonstration

Two related ISO standards provide globally acknowledged principles and a framework (ISO 14040:2006), and requirements and guidelines (ISO 14044:2006), for carrying out LCAs.

Following the standards, an LCA is performed in four major phases, which are interconnected to allow changes in one step based on new insights from another step:

1. **Goal and scope definition.** This phase defines the goal of the assessment, life cycle stages to be included, and quantitative functional unit of the product to be studied. The goal and scope depend on the intended use of study results. For example, life cycle stages would be different for (1) a cradle-to-gate study whose aim is to quantify the impacts of manufacturing a unit of softwood lumber and (2) a cradle-to-grave study that also covers the lumber's use and end-of-life treatment. Therefore, this phase of an LCA should be referenced to understand the methodological choices and intended application of the results.
2. **Inventory analysis.** This phase includes quantifying all environmentally significant inputs (material and energy flows) and outputs (environmental emissions) of the studied processes for the product system defined in the goal and scope phase. Analysis of these life cycle inventory flows provides preliminary data of the sources of GHG emissions.

3. **Impact assessment.** The life cycle inventory data are converted into potential environmental impacts with the help of characterization methods developed for different impact categories. For example, GHG emissions may be translated to global warming impacts based on an appraisal of GHG contributions to global warming.
4. **Interpretation.** In this phase, life cycle impact assessment results are interpreted with respect to the goal and scope definition and identified data gaps in order to provide recommendations for the intended audience.



Source: ISO 14040:2006.

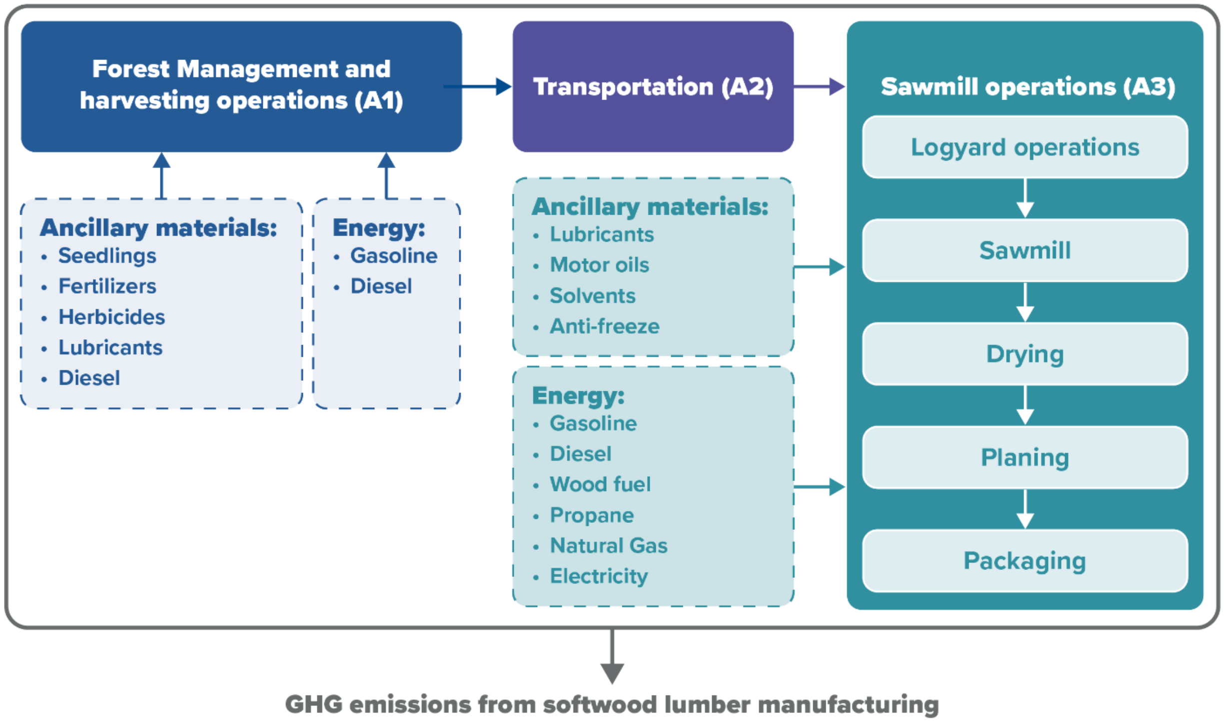
Figure 5B-3. Schematic of the LCA Phases and Their Interconnectedness

There are two types of LCA studies: attributional and consequential. An attributional LCA evaluates life-cycle environmental impacts associated with producing/using one functional unit of studied product or service. A consequential LCA evaluates change in environmental impacts due to a change in material inputs or service, comparing the outcomes under a baseline scenario with those under an alternate scenario. Consequential LCAs are typically used for policy changes: for example, evaluation of net GHG benefit of a policy that promotes wood use in the construction sector to replace high-carbon-emitting nonwood materials (e.g., steel and concrete).

Below is an example of an attributional LCA for an HWP: a study of softwood lumber by the Consortium for Research on Renewable Industrial Materials.

Example: Goal and Scope Definition

The Consortium's study sought to quantify the GHG emissions associated with 1 metric ton of softwood lumber manufactured in the U.S. Pacific Northwest, with a system boundary that spanned forest management and harvesting activities (cradle) to softwood lumber manufacturing and packaging (gate) for various end-use applications, including building construction. Key processes included within the identified system boundary are shown in figure 5B-4.



Source: Adapted from Puettmann (2020a).

Figure 5B-4. Cradle-to-Gate System Boundary for Softwood Lumber Manufacturing

Example: Inventory Analysis

The material and energy input–output data were collected for all the processes falling within the defined system boundary (figure 5B-4). Data from many softwood sawmills were collected, and weighted average values were estimated based on each mill's production capacity. The final aggregated inventory outputs from all the processes were converted to GHG emissions (including CO_2, CH_4, and N_2O) based on the functional unit of 1 metric ton of softwood lumber product.

Example: Impact Assessment

The impacts on environment from these GHG emissions were assessed by multiplying GHG inventory data for CO_2, CH_4, and N_2O by the pre-defined "characterization factors" referred to as GWPs, then added together, as shown in equation 5B-4 below:

Equation 5B-4: Impact Assessment

$$\sum_{i=CO_2,\, CH_4, N_2O} Inventory\ data\ (i) \times characterization\ factor\ (i) = Impact\ indicator\ results$$

The result, for 1 metric ton of softwood lumber product, averaged 0.161 metric ton of GHG emissions expressed as CO_2-eq.

Example: Interpretation

The impact assessment results obtained from the LCA study indicated that producing 1 metric ton of softwood lumber results in GHG emissions of 0.161 metric tons CO_2-eq from cradle to gate. The

LCA study also indicated that the sawmill operations were the largest contributor to these GHG emissions, followed by operations associated with management and harvesting activities, then transportation of roundwood to mills.

Potential Substitution Calculator

Estimates of the mass in metric tons carbon (from the harvest carbon calculator demonstration, above) are used for primary products as an input to estimate potential substitution effects. For example, 1,886.5 metric tons carbon of softwood lumber, produced from harvesting the 640 acres, with 7.5 MBF per acre, are first converted to tons CO_2-eq by multiplying by 3.67, then multiplied with the DF of 0.99 (described in section 5.2.2.1) to get 6,848 tons of total CO_2-eq reduction (substitution benefits) if substituting softwood lumber studs for steel studs in construction. Similar estimates are generated if any of the five other primary products from this land (hardwood lumber, plywood, oriented strandboard, nonstructural panels, and other industrial products) are produced. In this example, all primary products from harvesting the 640 acres, with 7.5 MBF per acre, could collectively reduce total GHG emissions by 11,384 metric tons CO_2-eq as construction substitution benefits.

For energy substitution potential, the calculator takes the emissions from fuelwood burned in year 0 and multiplies them by different numbers to show the potential displacement benefits of using this wood source instead of electricity, coal, oil, or gas. For example, total emissions from fuelwood burned in year 0 could displace 648 tons of fossil CO_2-eq emissions when wood energy replaces electricity, 1,651 tons of fossil CO_2-eq emissions when it replaces coal, 1,384 tons of fossil CO_2-eq emissions when it replaces heating oil, or 1,093 tons of fossil CO_2-eq emissions when it replaces natural gas. Emissions from "fuel and other" primary products, in year 0, are not explicitly shown in figure 5B-4. This is because most of those emissions are already folded into DFs for other primary products and are therefore mostly included in the product portion of the potential substitution calculator.

The calculator can also show the potential displacement from bark that was burned with energy capture. The 2,243 tons CO_2-eq emissions generated from burning bark, assuming the Smith et al. (2006) carbon content and use mill residue heating potential, could reduce the totals by 599, 1,525, 1,279, and 1,010 tons of fossil CO_2-eq emissions assuming it replaces electricity, coal, heating oil, or natural gas, respectively.

For purposes of demonstration, the wood product construction total (11,384 t CO_2-eq) and the most conservative energy (electricity) numbers (648 + 599 = 1,247 t CO_2-eq) are shown on the "Forest Management & HWP Results" tab as maximum substitution potential.

Products Produced from Harvest Calculato	Softwood Lumber Carbon (Mg)	Hardwood Lumber (Mg)	Softwood Plywood (Mg)	Hardwood Plywood (Mg)	OSB (Mg)	Non-structural panels (Mg)	Other industrial products (Mg)	Wood Pulp (Mg)	Total Processed Storage (Mg)	Fuelwood Emissions by this year (Mg)	Percent of HWP Emitted by this year
Amounts (Mg = Metric Tons)	1,886.500	-	19.299	-	-	96.496	400.459	347.386	2,750.140	662	50%
	Results - Potential Cradle to Gate Substitution Factors and Effects (C02E)										
	Displacement Factors										
Alternative Products Produced	Alternative Product: Steel Studs	Alternative Product: Doors	Alternative Product: Stutural Elements	Alternative Product: Stutural Elements	Alternative Product: Stutural Elements	Alternative Product: Non-Stuctural Elements	Alternative Product: Non-Stuctural Elements	Alternative Product: Non-Construction Uses	Total	Electricity	
Substitution factors (CO2e emissions avoided from wood substitution of non-wood fossil-based alternatives, estimated for cradle-to-gate life stages (Here negative implies reduced emissions potential)	-0.99	-2.29	-1.3	-1.3	-1.3	-1.6	-1.6	-1.2		-0.267	
Displacement Benefits (Here negative implies reduced emissions potential; this differs from how positive and negative are typically shown in LCA results, but it is consistent with our use of negative and positive elsewhere in our results.)	(6,848)	-	(92)	-	-	(566)	(2,349)	(1,528)	**(11,384)**	**(648)**	
										Anthracite Coal	
										-0.68	
										(1,651)	
										Heating Oil	
										-0.57	
										(1,384)	
										Natural Gas	
										-0.45	
										(1,093)	

Bark biogenic emissions year of harvest with energy capture (Co2E)	Bark biogenic emissions year of harvest without energy capture (CO2E)	Percent of Bark emitted by this year
2,243	1,424	100%
Results Potential Bark Substitution		
Electricity		
-0.267		
(599)		
Anthrocite Coal		
-0.68		
(1,525)		
Heating Oil		
-0.57		
(1,279)		
Natural Gas		
-0.45		
(1,010)		

	Results - Emissions Outside the Biogenic HWP Carbon Storage or Flux								
Products Produced from Harvest Calculato	Softwood Lumber Carbon (Mg)	Hardwood Lumber (Mg)	Softwood Plywood (Mg)	Hardwood Plywood (Mg)	OSB (Mg)	Non-structural panels (Mg)	Other industrial products (Mg)	Wood Pulp (Mg)	Total Processed Emissions without Wood Pulp
Metric Tons of Products Produced (t)	1,886.500	-	19.299	-	-	96.496	400.459	347.386	
Metric Tons CO2e of Products Produced (t	6,917.166	-	70.764	-	-	353.819	1,468.350	1,273.749	
LCA Quantified GHG Emissions from Cultivation and Harvest (t CO2eq)	0.015	0.024	0.077	0.077	0.071	0.205	0.055	No Data	
Results	104	-	5	-	-	73	81		262
LCA Quantified GHG Emissions from Transportation to the Mill (t CO2eq)	0.012	0.028	0.012	0.012	0.006	0.006	0.037	No Data	
Results	83	-	1	-	-	2	54		140
LCA Quantified GHG Emissions from Wood Processing (t CO2eq)	0.061	0.096	0.173	0.173	0.136	0.241	0.056	No Data	
Results	422	-	12	-	-	85	82		602
Total LCA Quantified GHG Emissions from Wood Cultivation, Harvest, Transportation and Processing (t CO2eq)	0.09	0.15	0.26	0.26	0.21	0.45	0.15	No Data	
Results	**609**	**-**	**19**	**-**	**-**	**160**	**217**		**1,004**

Figure 5B-5. Potential Substitution Calculator Demonstration

5-B.3 Wildfire and Prescribed Fire Methods

5-B.3.1 Rationale for Method

Given the escalating scale and severity of fire seasons, particularly across the U.S. West, the demand for information to estimate wildfire-related GHG emissions and inform fuel management actions is significant. However, quantifying avoided wildfire emissions from forest management activities such as fuel treatments requires highly complex models that consider the GHG-related implications of various forest management activities (including prescribed fire, fuel for harvest activities, and the long-term fate of HWPs); a probabilistic accounting for future fire likelihood and intensity; and a long-term model of the fate of burned carbon stocks, forest regrowth/regeneration potential, and subsequent disturbance risks.

For Level 1, the methodology offers a means to quantify an important but limited part of more indepth analysis of avoided wildfire emissions. Level 1 is a starting point for land managers seeking to understand the immediate impacts of low-severity prescribed burns and compare them to GHG impacts from higher severity fire events by compiling estimates of forest biomass combustion derived from simulations using FIA data as input to the FFE-FVS.

For Level 3, FFE-FVS was chosen as the model because it can simulate stand, fuel, and carbon dynamics over time while also being able to incorporate FIADB (Burrill et al., 2021) plot data within its modeling approach—that is, it is dynamically connected to contemporary forest resource information via FIA data. These are advantages over the FOFEM model prescribed in the 2014 guidelines (though FFE-FVS and FOFEM use many of the same internal algorithms for estimating and fuel consumption and emissions and a similar tree mortality approach).

FFE-FVS is a powerful predictive tool, offering a more advanced means to simulate fire impacts than simpler algorithms such as those in the *2006 IPCC Guidelines for National GHG Inventories* (IPCC, 2006) while also enabling simulation of various management approaches (e.g., clear-cut vs. timber stand improvement activities). In totality, this approach facilitates connections among national databases, modeling/simulation tools, and region/forest type configurations while acknowledging much work remains in refining approaches to estimating probabilities of future fire occurrence, forest management activities, and fuel dynamics under global change scenarios.

5-B.3.2 Technical Documentation

The forest types in this chapter correspond to the "forest type groups" described in the FIADB phase 2 user guide (Burrill et al., 2021, appendix D). These forest types are also listed explicitly in table 5B-11.

Table 5B-11. FIA Forest Type Group Names, Codes and Associated Forest Types

White/Red/Jack Pine Group	100
Jack pine	101
Red pine	102
Eastern white pine	103
Eastern white pine/eastern hemlock	104
Eastern hemlock	105
Spruce/Fir Group	**120**
Balsam fir	121
White spruce	122
Red spruce	123
Red spruce/balsam fir	124
Black spruce	125
Tamarack	126
Northern white-cedar	127
Longleaf/Slash Pine Group	**140**
Longleaf pine	141
Slash pine	142
Loblolly/Shortleaf Pine Group	**160**
Loblolly pine	161
Shortleaf pine	162
Virginia pine	163
Sand pine	164
Table Mountain pine	165
Pond pine	166
Pitch pine	167
Spruce pine	168

Oak/Pine Group	400
Eastern white pine/northern red oak/white ash	401
Eastern redcedar/hardwood	402
Longleaf pine/oak	403
Shortleaf pine/oak	404
Virginia pine/southern red oak	405
Loblolly pine/hardwood	406
Slash pine/hardwood	407
Other pine/hardwood	409
Oak/Hickory Group	**500**
Post oak/blackjack oak	501
Chestnut oak	502
White oak/red oak/hickory	503
White oak	504
Northern red oak	505
Yellow-poplar/white oak/northern red oak	506
Sassafras/persimmon	507
Sweetgum/yellow-poplar	508
Bur oak	509
Scarlet oak	510
Yellow-poplar	511
Black walnut	512
Black locust	513
Southern scrub oak	514
Chestnut oak/black oak/scarlet oak	515
Red maple/oak	519
Mixed upland hardwood	520

White/Red/Jack Pine Group	100
Pinyon/Juniper Group	**180**
Eastern redcedar	181
Rocky Mountain juniper	182
Western juniper	183
Juniper woodland	184
Pinyon/juniper woodland	185
Douglas-Fir Group	**200**
Douglas-fir	201
Port-Orford-cedar	202
Ponderosa Pine Group	**220**
Ponderosa pine	221
Incense-cedar	222
Jeffrey pine/Coulter pine/bigcone Douglas-fir	223
Sugar pine	224
Western White Pine Group	**240**
Western white pine	241
Fir/Spruce/Mountain Hemlock Group	**260**
White fir	261
Red fir	262
Noble fir	263
Pacific silver fir	264
Engelmann spruce	265
Engelman spruce/subalpine fir	266
Grand fir	267
Subalpine fir	268
Blue spruce	269
Mountain hemlock	270
Alaska yellow-cedar	271
Lodgepole pine group	**280**
Lodgepole pine	281
Hemlock/Sitka spruce group	**300**
Western hemlock	301
Western redcedar	304

Oak/Pine Group	400
Oak/Gum/Cypress Group	**600**
Swamp chestnut oak/cherrybark oak	601
Sweetgum/Nuttall oak/willow oak	602
Overcup oak/water hickory	605
Atlantic white-cedar	606
Baldcypress/water tupelo	607
Sweetbay/swamp tupelo/red maple	608
Elm/Ash/Cottonwood Group	**700**
Black ash/American elm/red maple	701
River birch/sycamore	702
Cottonwood	703
Willow	704
Sycamore/pecan/American elm	705
Sugarberry/hackberry/elm/green ash	706
Silver maple/American elm	707
Red maple/lowland	708
Cottonwood/willow	709
Oregon ash	722
Maple/Beech/Birch Group	**800**
Sugar maple/beech/yellow birch	801
Black cherry	802
Cherry/ash/yellow-poplar	803
Hard maple/basswood	805
Elm/ash/locust	807
Red maple/upland	809
Aspen/Birch Group	**900**
Aspen	901
Paper birch	902
Balsam poplar	904
Alder/maple group	910
Red alder	911
Bigleaf maple	912
Western Oak Group	**920**
Gray pine	921
California black oak	922
Oregon white oak	923

White/Red/Jack Pine Group	100
Sitka spruce	305
Western larch group	**320**
Western larch	321
Redwood group	**340**
Redwood	341
Giant sequoia	342
Other Western Softwoods Group	**360**
Knobcone pine	361
Southwest white pine	362
Bishop pine	363
Monterey pine	364
Foxtail pine/bristlecone pine	365
Limber pine	366
Whitebark pine	367
Miscellaneous western softwoods	368
California Mixed Conifer Group	**370**
California mixed conifer	371
Exotic Softwoods Group	**380**
Scotch pine	381
Australian pine	382
Other exotic softwoods	383
Norway spruce	384
Introduced larch	385

Oak/Pine Group	400
Blue oak	924
Deciduous oak woodland	925
Evergreen oak woodland	926
Coast live oak	931
Canyon live oak/interior live oak	932
Tanoak/Laurel Group	**940**
Tanoak	941
California laurel	942
Giant chinkapin	943
Other Western Hardwoods Group	**950**
Pacific madrone	951
Mesquite woodland	952
Cercocarpus woodland	953
Intermountain maple woodland	954
Miscellaneous western hardwoods woodland	955
Tropical Hardwoods Group	**980**
Sable palm	981
Mangrove	982
Other tropical	989
Exotic Hardwoods Group	**990**
Paulownia	991
Melaleuca	992
Eucalyptus	993
Other exotic hardwoods	995
Nonstocked	**999**

Results are presented in two tables: the FIRE table and the CARBON table (combined in the "Fire_Lookup" tab in the Excel workbook).

- The FIRE table provides immediate fire effects—biomass consumed, carbon emitted, GHG emissions, and postfire total stand carbon—which are binned into lookup tables based on FIA forest type group, geographic region, and fire severity. The lookup tables provide best-estimate (median) values and uncertainty appraisals (25 percent and 75 percent quantiles) of the metrics for each bin. An excerpt from the FIRE table for the Rocky Mountain South region is given in table 5B-13.
- The CARBON table provides prefire and immediate postfire carbon pool estimates. As with the FIRE table, the carbon pool estimates are aggregated into lookup tables based on FIA

forest type group, geographic region, and fire severity. Table 5B-14 provides an excerpt from the CARBON table for low-severity fire in the Rocky Mountain South Region.

For the conterminous United States, over 350,000 different combinations of region, forest type, and fire conditions were simulated. Carbon pool and GHG emission estimates for these simulations can be queried to produce reports using the Excel workbook.

GHG Pollutant Emission Factors, GWP, and CO_2-eq

Pollutant emission factors (PEFs) provide the mass of a pollutant emitted per unit mass of biomass carbon burned (g of pollutant per kg of carbon). Emissions of GHG *x*—denoted E_x—in units kg of *x*/hectare are calculated as:

Equation 5B-5: Pollutant Emission Factors

$$E_x = 0.001 \times PEF_x \times EC$$

Where:

E_x	=	emission rate of a given GHG (kg/ha)
0.001	=	PEF conversion factor (g/kg to kg/kg)
PEF_x	=	mass of a pollutant emitted per mass of biomass carbon burned (g pollutant/kg C)
EC	=	total carbon emitted (volatilized) by fire (kg C/hectare)

The CO_2 PEF includes carbon monoxide (CO), which accounts for up to 10 percent of volatilized carbon (Permar et al., 2021). CO resides in the atmosphere for a few months before being removed, primarily by gas phase oxidation to CO_2 (Khalil and Rasmussen, 1990; Cordero et al., 2019). Therefore, CO emissions are treated as CO_2 emissions and the PEF for CO_2 includes emitted CO. Note that, through atmospheric chemical reactions, CO indirectly affects the concentrations of other GHGs, and it has been proposed that CO emissions should have a GWP; see Myhre et al. (2013) for details. The PEFs for southern fires were used for the south central and southeastern regions, and the western/northern PEFs were used for all other regions. The PEFs for western and northern fires are based on airborne measurements of wildfires across the western United States. The PEFs may underestimate CH_4 emissions, since airborne measurement platforms may under-sample long-term smoldering of duff and coarse woody debris, which is characterized by a higher CH_4 PEF than other combustion processes (see Urbanski, 2014). The PEF for southern wildland fires synthesizes airborne and ground-based emission measurements from prescribed fires in southeastern forests (Urbanski, 2014). The CH_4 PEF will likely underestimate CH_4 emissions for fires involving significant peat/organic soil smoldering (Urbanski, 2014).

Table 5B-12. GHG PEFs and GWPs

GHG	PEF (g/kg C)[a]		GWP[b]
	Southern	Northern/Western	
CO_2	3,450	3,310	1
CH_4	4.6	13	28
N_2O	0.32	0.32	265
CO_2-eq	3,660	3,730	—

[a] Myhre et al. (2013).

[b] IPCC Fifth Assessment Report (IPCC, 2013).

Table 5B-13. Data Fields of the FIRE Table: Estimated Carbon and GHG (CO_2, CH_4, N_2O) Emissions, Biomass Consumed, and Postfire Total Stand Carbon

Column	Variable Name	Units	Description
1	region	None	Geographic region code
2	forgrp	None	FIA forest type group code
3	fire_sev	None	Fire severity code
4	Total_Stand_Carbon_50%	Mg carbon per hectare	Best estimate (median) of total stand carbon postfire
5	Total_Stand_Carbon_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of total stand carbon postfire
6	Total_Stand_Carbon_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of total stand carbon postfire
7	Carbon_Released_From_Fire_50%	Mg carbon per hectare	Best estimate (median) of carbon emitted by fire
8	Carbon_Released_From_Fire_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon emitted by fire
9	Carbon_Released_From_Fire_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon emitted by fire
10	Total_Consumption_50%	Mg biomass per hectare	Best estimate (median) of biomass consumed by fire
11	Total_Consumption_25%	Mg biomass per hectare	Lower bound estimate (25th percentile) of biomass consumed by fire
12	Total_Consumption_75%	Mg biomass per hectare	Upper bound estimate (75th percentile) of biomass consumed by fire
13	ECO_2_50%	Mg CO_2 per hectare	Best estimate (median) of CO_2 emitted by fire
14	ECO_2_25%	Mg CO_2 per hectare	Lower bound estimate (25th percentile) of CO_2 emitted by fire
15	ECO_2_75%	Mg CO_2 per hectare	Upper bound estimate (75th percentile) of CO_2 emitted by fire
16	ECH_4_50%	Mg equivalent CO_2 per hectare	Best estimate (median) of CH_4 emitted by fire
17	ECH_4_25%	Mg equivalent CO_2 per hectare	Lower bound estimate (25th percentile) of CH_4 emitted by fire
18	ECH_4_75%	Mg equivalent CO_2 per hectare	Upper bound estimate (75th percentile) of CH_4 emitted by fire
19	EN_2O_50%	Mg equivalent CO_2 per hectare	Best estimate (median) of N_2O emitted by fire
20	EN_2O_25%	Mg equivalent CO_2 per hectare	Lower bound estimate (25th percentile) of N_2O emitted by fire
21	EN_2O_75%	Mg equivalent CO_2 per hectare	Upper bound estimate (75th percentile) of N_2O emitted by fire
22	ECO_2equiv_50%	Mg equivalent CO_2 per hectare	Best estimate (median) of total GHG emitted by fire
23	ECO_2equiv_25%	Mg equivalent CO_2 per hectare	Lower bound estimate (25th percentile) of total GHG emitted by fire
24	ECO_2equiv_75%	Mg equivalent CO_2 per hectare	Upper bound estimate (75th percentile) of total GHG emitted by fire

Table 5B-14. Data Fields of the CARBON Table: Estimated Prefire, Postfire, and Change in Carbon Pools (Mg C/ha)

Column	Variable Name	Units	Description
1	region	None	Geographic region code
2	forgrp	None	FIA forest type group code
3	fire_sev	None	Fire severity code
4	status	None	Prefire, postfire, or change
5	Aboveground_Total_Live_50%	Mg carbon per hectare	Best estimate (median) of carbon in total aboveground live biomass
6	Aboveground_Total_Live_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in total aboveground live biomass
7	Aboveground_Total_Live_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in total aboveground live biomass
8	Belowground_Live_50%	Mg carbon per hectare	Best estimate (median) of carbon in belowground live biomass
9	Belowground_Live_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in belowground live biomass
10	Belowground_Live_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in belowground live biomass
11	Belowground_Dead_50%	Mg carbon per hectare	Best estimate (median) of carbon in belowground dead biomass
12	Belowground_Dead_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in belowground dead biomass
13	Belowground_Dead_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in belowground dead biomass
14	Standing_Dead_50%	Mg carbon per hectare	Best estimate (median) of carbon in total standing dead biomass
15	Standing_Dead_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in standing dead biomass
16	Standing_Dead_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in standing dead biomass
17	Forest_Down_Dead_Wood_50%	Mg carbon per hectare	Best estimate (median) of carbon in DDW
18	Forest_Down_Dead_Wood_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in DDW
19	Forest_Down_Dead_Wood_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in DDW
20	Forest_Floor_50%	Mg carbon per hectare	Best estimate (median) of carbon in forest floor
21	Forest_Floor_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in forest floor
22	Forest_Floor_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in forest floor
23	Forest_Shrub_Herb_50%	Mg carbon per hectare	Best estimate (median) of carbon in shrub and herb
24	Forest_Shrub_Herb_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of carbon in shrub and herb

Column	Variable Name	Units	Description
25	Forest_Shrub_Herb_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of carbon in shrub and herb
26	Total_Stand_Carbon_50%	Mg carbon per hectare	Best estimate (median) of total stand carbon
27	Total_Stand_Carbon_25%	Mg carbon per hectare	Lower bound estimate (25th percentile) of total stand carbon
28	Total_Stand_Carbon_75%	Mg carbon per hectare	Upper bound estimate (75th percentile) of total stand carbon

5-B.4 Urban Forest Management

5-B.4.1 Rationale for Method

The rationale for the i-Tree methods is grounded in i-Tree's dynamic development, expansion, and refinement. Since its introduction in 2006, the i-Tree program (including methodologies, databases, and software) has focused on urban ecosystem service evaluation and urban forest management guidance by providing the environmental benefits and services of urban and community trees and forests, including carbon storage and sequestration. Since its origin, i-Tree continues to be updated, expanded, and refined with new science and data: the current version is a consistent, yet substantial improvement and update over the approach recommended in the 2014 guidelines. This continued development in the i-Tree program will allow users to get the most up-to-date science and improved carbon accounting, as well as many other tree and forest benefit values, now and into the future.

Appendix 5-C: Summary of Research Gaps for Forestry Systems

5-C.1 General Interactions

There may be interactions between biological and physical processes that are affected by forest management treatments or natural disturbances, such as the albedo effect, evaporation, and turbulence (Bright et al., 2017). For example, the Earth's albedo is the fraction of sunlight and energy it reflects back into the atmosphere. Snow, with its light color, has high albedo; dark land cover absorbs sunlight energy and has a low albedo effect. In the context of forest management and its effects on climate change, trees (depending on species and density) may have a low albedo, contributing to a warmer surface temperature. This suggests that albedo changes due to tree planting and forest management could counteract anticipated climate benefits in the absence of other biophysical conditions. This is an emerging field of study, involving complex relationships that depend on many factors and biophysical interactions are not included in these methods. Beyond the estimation of climatic impacts, the calculation of ecosystem co-benefits (e.g., water, wildlife habitat, cultural values) is beyond the objective of these guidelines, though there are recognized interactions between these ecosystem functions and GHG fluxes (e.g., impacts of belowground biodiversity on tree growth (Prescott and Grayston, 2023)).

5-C.2 Silviculture and Improved Forest Management

The intersection of silviculture (i.e., the intentional manipulation of ecosystem carbon across varying combinations of tree species and structures), the complexities associated with forest carbon estimation (e.g., for soils and/or dead wood), and uncertain future climates suggest a litany of opportunities to increase the accuracy and associated applied knowledge of climate adaptation/mitigation and forest management efforts. Although a full examination of this topic is beyond the purview of this chapter, some of the largest research opportunities are in stand management projection (i.e., growth and yield modeling) and development of adaptive silviculture for climate change applications with a focus on carbon implications.

To refine estimates of emissions at harvest, further studies and data are needed to characterize transfers of live to dead biomass carbon and soil carbon pools, emission rates, and what proportion of the total biomass ultimately enters the HWP pool. More data would enable a more complete and connected quantification of the impacts of forest management from ecosystems to products in use to SWDS. In addition, the variety of site preparation techniques commonly employed during even-aged silvicultural systems (including root-raking, roller drum chopping, chemical applications, and/or fertilization) should be quantified in entity-scale guidelines for more complete assessments of GHG flux.

Finally, a more comprehensive inclusion of the variety of silvicultural systems from uneven-aged to even-aged is a necessity for further emission estimates refinements, especially as the full breadth of such management approaches may be needed for society to adapt to future climate change. Perhaps objective classification of management techniques and associated identification across United States forest ecosystems, coupled with spatially explicit estimates of forest change, would empower adaptation, improve market opportunities, and reduce uncertainty in forest carbon projections for policymakers.

5-C.3 Harvested Wood Products

5-C.3.1 Data Gaps

In a number of cases, this chapter applies data that have not been updated for long periods (e.g., 1998 data to allocate harvests to primary wood products, 2009 data to allocate primary products to end uses). Landfill assumptions for paper in table 5B-13 are based on Freed and Mintz (2003), cited in Smith et al. (2006) notes. Landfill assumptions for solid wood products are based on U.S. EPA WARM, indicating 88 percent of carbon lumber (used for solid wood) is stored permanently; this is a lumber figure only.

The DFs for emerging HWP use (e.g., mass timber products, wood energy products) need to be defined to quantify impactful GHG reduction benefits over time. More LCA studies and national or regional timber product output data, especially for these emerging HWPs, will be needed. Additionally, the long-term fates, product yield, end uses, and end-of-life fates for HWP are needed. HWP and associated industries/uses may need to be considered as an ecosystem unto itself: perhaps comprehensive entity-scale guidelines can only be realized by equally matching the sophistication of ecosystem carbon assessment with the tightly coupled HWP "ecosystem."

5-C.3.2 Research Gaps

Decay Function Evaluation

This chapter provides both the conventional (i.e., exponential) and alternative chi-square functions to represent the lifespans for long-lived products and their decay in landfills in the production approach. However, refined data in this topic area would be very helpful as a tool to mitigate climate change, especially as carbon markets—which normally rely on projections of carbon storage—continue to grow.

Substitution Benefits Evaluation

Underlying differences in wood and nonwood products should be characterized with more data on manufacturing technologies and more precision in choosing equivalent alternatives. The LCA studies for both wood and nonwood products, used to assess the substitution factors, have inherent heterogeneity and uncertainties, and are not expected to remain constant (Harmon, 2019). The Level 2 and 3 updates in substitution factors aim to reduce this variability by collecting more data on GHG emissions. The choice of allocation method for distributing GHG emissions between main products and coproducts and the inclusion of life cycle stages in the system boundary would be critical (Keith et al., 2015). These choices would greatly influence the estimated DFs and subsequent interpretations of the substitution benefits.

Because uncertainties exist in the currently reported HWPs' DFs, more research is needed to define individualized DFs for every possible HWP substitution; then, more accurate substitution benefits can be quantified. This need includes bark substitution factors. Emerging mass timber products, such as cross-laminated timber, have been adopted into new building construction and remodeling. For nonresidential and mid- to high-rise building construction, the precise DFs for cross-laminated timber and other mass timber products will be critical to quantify the substitution impacts in the building sector.

The biomass energy substitution benefits could be enhanced if forest residues, thinned trees, or other fire-reduction-induced biomass were collected for energy substitutions. Research is needed to quantify the impacts with the LCA—in particular, to include benefits and costs in other realms (such as wildlife habitat and nutrient cycling)—to maximize potential GHG displacement benefits from using these sources of woody biomass.

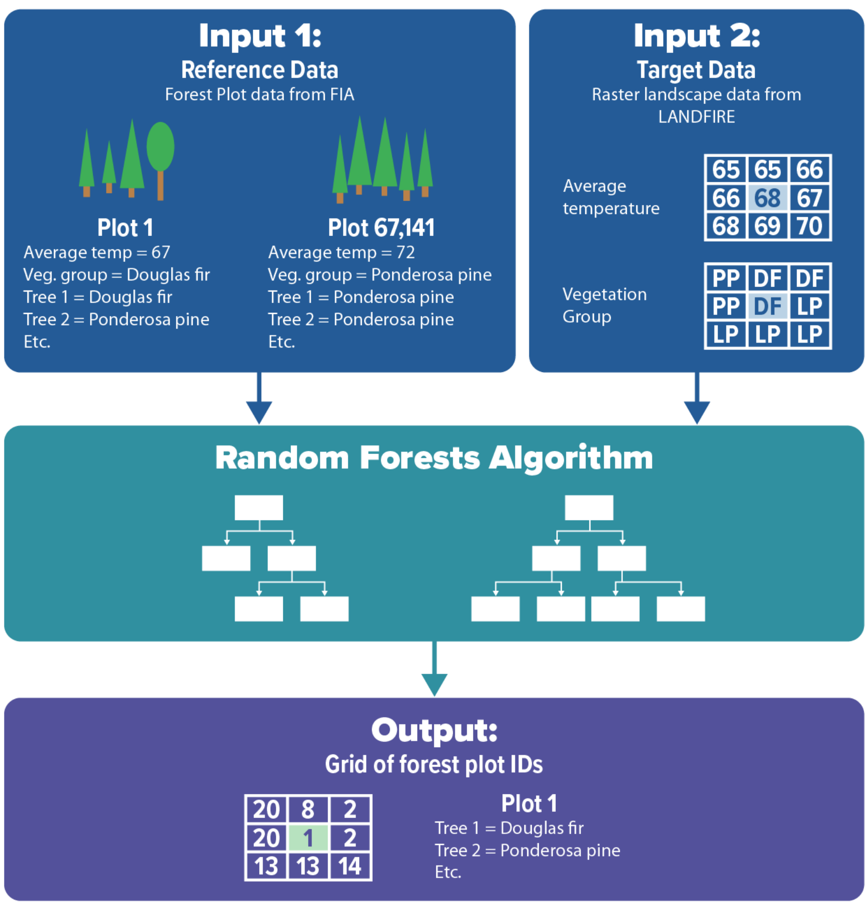
5-C.4 Wildfire and Prescribed Fire Methods

The following subsections outline known future improvements, due to current research and understanding gaps, to the methods provided in this chapter.

5-C.4.1 Spatially Explicit GHG Emissions

The current methodology provides estimates of GHG emissions and carbon pool fluxes attributable to wildland fire, aggregated by region and forest type. Improved estimates could be provided through a spatially explicit product based on TreeMap (Riley et al., 2021), a continental-U.S.-wide gridded dataset linked to FIA forest plots. TreeMap may be a solution for users who need spatially explicit estimates of carbon pool and GHG fluxes and have access to GIS analyst skills.

Figure 5C-1 shows a potential implementation of a TreeMap-based GHG emission estimation method. In the figure, the TreeMap dataset (Riley et al., 2021) assigns an FIA plot to each 30-by-30-meter pixel based on a suite of predictor variables including topography, vegetation, biophysical conditions, and disturbance.



Source: Riley et al. (2021).

Figure 5C-1. Workflow for Generating Maps Using TreeMap Data

Each FIA plot identifier is linked to a list of trees and their characteristics, including species, dbh, and height, and many plots have information on DDW as well. Each color in the map corresponds to a unique plot. Cadastral boundaries can be overlaid with the TreeMap to extract information about trees and DDW for a given parcel; from these characteristics, carbon can be estimated in FFE-FVS.

5-C.4.2 Postfire Carbon Trajectories

Another major improvement to the methodology presented in this section would be the addition of postfire (and no-fire) carbon pool time-series. FVS could be used to simulate postfire forest regeneration and growth for 50–100 years to provide long-term carbon trajectories for the recovering forest (Raymond et al., 2015). FVS simulations run under a no-fire scenario would provide a baseline carbon trajectory that, when compared with various fire scenarios, would provide estimates of indirect carbon emissions. The generation of long-term forest trajectories with FVS does not represent a major technical undertaking relative to the methods used to develop the immediate fire-induced GHG emissions presented in this section. However, uncertainties in the reliability of postfire FVS forest simulations, future site disturbances, and climate change make the interpretation and use of such trajectories very challenging.

Postfire forest regeneration and growth simulated by FVS is highly uncertain, in large part due to gaps in current scientific understanding of these processes, as well as uncertainty in factors driving regeneration, such as timing and amount of postfire precipitation and drought. The literature varies in the response of carbon trajectories postfire, especially in lower-severity prescribed fires and other fuel reduction methods. Many studies show a carbon benefit a few decades after a prescribed fire (Hurteau et al., 2016; Liang et al., 2018; Loudermilk et al., 2016; McCauley et al., 2019), but others show it may take longer to recover the carbon lost from even low-severity fires (Ager et al., 2010; Campbell et al., 2012; Spies et al., 2017). This is one of the largest sources of uncertainty on the overall impact of wildfire on carbon storage, because whether carbon sequestration is suppressed for 1 year or more than 10 years has a large effect on long-term carbon storage.

Other challenges in modeling postfire carbon trajectories include forecasting the timing and severity of future fires, which will be affected by climate change. Trajectories in future climate are themselves uncertain and will also have effects on forest structure, including regeneration failure in some areas, as well as increased susceptibility to insects and disease due to drought stress. Finally, the assessment of GHG emissions from pile burning and estimation of future avoided wildfire emissions (i.e., catastrophic emissions) warrants future research to empower decision making in the context of managing fire vs. implicitly accepting emissions from future wildfires.

5-C.5 Urban Forest Management and/or Trees Outside Forests

Approaches to quantify carbon storage and annual sequestration from urban forest management can also be improved with more field data collection in urban areas, and with model and method improvements related to carbon estimation. Support of ongoing and initiation of new research focused on improving and updating the allometric equations in i-Tree is warranted. More research is needed on the applicability of forest-derived equations to urban trees. In addition, more urban tree growth data are needed to better understand regional variability of urban tree growth under differing site conditions (e.g., tree competition) for better annual sequestration estimates. Average regional growth estimates are used based on limited measured urban tree growth data standardized to length of growing season and crown competition.

Estimates of maintenance emissions and altered building energy use effects need further evaluation and refinement to advance more complete carbon accounting while also improving the scientific community's understanding of relationships between trees and building energy usage. Research on urban forest management activities should also include more carbon and environmental benefit analysis of urban biomass utilization and waste, aligning with the methods developed for the section on HWPs, LCA, and substitution (section 5.2.2).

For both photo interpretation and online geospatial database methods, supporting both ongoing and new high-resolution aerial imagery and land cover projects throughout the country will improve those methods. In addition, further development of i-Tree tools is needed to allow a finer-scale user selection (smaller than census block groups) for carbon accounting.

Finally, between urban and rural forests there are a spectrum of trees across the landscape for which associated GHG benefits can be calculated but are not included in this version. For example, the use of trees in agroforestry systems, silvopasture, or even nut/fruit tree orchards is somewhere between the land uses of forests and agricultural systems. It should not be overlooked; analytical procedures such as small area estimation (Prisley et al., 2021), as well as the use of high-resolution remotely sensed information, may advance understanding in this area.

5-C.6 Uncertainty Data Gaps

While there are some known default values (see appendix 5-B), quantifying uncertainty as an implicit, explicit-model, or explicit-measurement-based method, as discussed in chapter 8, requires more information than was available for this version of the report. To encourage transparency, USDA noted this gap within the chapter and hopes to prioritize this improvement in the next version of the report.

Broadly, there is often uncertainty associated with estimates of forest carbon, such that even at large scales (e.g., State-level), the power to detect statistically significant changes in forest carbon stocks is limited to major disturbances (Westfall et al., 2013). Compounding the sampling error often associated with forest inventories, there is measurement and model error that may not be known. Users of any inventories, lookup tables, or models should remain aware of these potential errors as they apply information.

Perhaps some of the most needed improvements are for individual tree volume/biomass equations, especially for traditionally noncommercial species. Further, there is considerable uncertainty in summarizing the carbon content among the various forest carbon pools (e.g., belowground to forest floor) found across a diversity of forest ecosystems (e.g., tropical to boreal) in the United States. SOC is among these pools, for which limited national-scale data exist to support consistent forest management decision making. Although the soil carbon pool is not expected to change quickly in comparison to live tree pools, in many areas of the United States it is the largest carbon stock (e.g., in northern Minnesota). Beyond reducing the uncertainty associated with estimates of carbon pools, there is ongoing research to refine understanding of the effects of disturbance and climate change on carbon pools.

Another significant area of uncertainty is the ability to influence or predict the influence of forest management activities outside the boundaries of the forest management intervention (e.g., leakage effects). Likewise, there is high variability in estimating substitution effects, especially looking to a future where material manufacturing technologies evolve to be less fossil-fuels-intensive.

5-C.7 Forest Carbon Pool Estimation

As identified through this work and noted in prior discussion, continued research is needed on estimating individual forest carbon pools, especially because they are expected to dynamically respond to climate change. Soil organic carbon is often the largest carbon pool in many forest ecosystems, so its quantification—especially in terms of potential change due to forest management interventions—is paramount. These guidelines omit soil carbon fluxes only because of the lack of sufficient data and research to comprehensively characterize soil carbon response to forest management practices. Likewise, the pools of belowground biomass (e.g., coarse roots) and stumps are critical to informing GHG assessments of forest management activities, especially those related to short-rotation, even-aged silvicultural systems. As with procedures enacted to derive Level 1 approximations of other forest carbon pools (e.g., HWPs), future efforts could apply basic decay functions to belowground biomass and stump pools subsequent to harvests.

As the prior version of these guidelines used the component ratio method (Woodall et al., 2011) to estimate individual tree volume/biomass and this version uses the newly refined NSVB estimators (Westfall et al., 2023), it is expected that allometric refinements will continue through time such that future guideline versions may consider adopting refined carbon fractions and improved individual tree attribute models.

Perhaps the most important advance to be developed in estimating forest carbon pools is the dynamic estimation of forest carbon attributes for any given entity (e.g., forest stand or project) in geospatial systems for rapid knowledge development and transfer. This version of the guidelines derives estimates of forest ecosystem pools by broad domains (e.g., region and forest type) from the national FIADB, such that the associated lookup tables can be rapidly updated via code pipelines between the workbook and the FIADB. Future versions of guidelines and/or applications are expected to be even more dynamic but in a spatially explicit manner. Advances in the research and application of small-area estimation techniques (Prisley et al., 2021) as an approach additional to imputation techniques (Riley et al., 2021) may yield not only authoritative, gridded datasets of forest carbon attributes but also more explicit characterization of error structures.