Wood as a Renewable and Sustainable Resource

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The mission of the USDA Forest Service is to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. All Forest Service activities, conducted through the National Forest System, Forest Service Research and Development, and State and Private Forestry, are intended to help sustain forests and grasslands now and into the future. The Forest Service manages over 193 million acres (78 million hectares) of National Forests and Grasslands for sustainable multiple uses to meet the diverse needs of people, ensure the health of our natural resources, provide recreational opportunities, manage wildfire, guard against invasive threats, and work with State and private forest landowners, cities and communities, and international cooperators (USDA Forest Service 2018, 2020a).

To support these land management goals and to engage with State and private agencies, the Forest Service conducts leading-edge research on all aspects of forestry, rangeland management, and forest resource utilization through a network of research stations, the Forest Products Laboratory, and the International Institute of Tropical Forestry. A significant number of publications and science delivery activities are completed annually that share key science completed by the Forest Service and their partners. For the Forest Products Laboratory, the *Wood Handbook–Wood as an Engineering Material*, is published every decade and provides the latest science and information for wood materials and their product applications.

There is an inherent connection between forestry and forest products. One key to maintaining healthy and resilient forests is to have product and market options for all materials. As emphasized in the following chapters of this publication, wood materials can be processed into a wide range of materials, including lumber, engineered composites, carbonized materials, and cellulosic nanomaterials. Market connections are essential in supporting forest management. Timber sales and other removals of forest products support agency strategic objectives to foster resilient, adaptive ecosystems to mitigate wildfire risk and climate change, produce carbon-storing sustainable materials, and strengthen communities (USDA Forest Service 2020b). Markets for sustainably harvested forest products also help keep management costs down by generating revenue.

Finally, the connection between forest management and forest product markets improves local and national economies. Currently, the U.S. forest products industry accounts for approximately 4% of the total U.S. manufacturing GDP, manufacturing nearly $300 billion in products annually. It employs approximately 950,000 people and supports a payroll of about $50 billion annually, making it amongst the top 10 manufacturing sector employers in 45 states (AF&PA 2020a,b; Brandeis and others 2021).

Sustainable Forestry and Measures

The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 (P.L. 93-378, 88 Stat. 475) requires the Secretary of the U.S. Department of Agriculture to conduct decadal assessments of the Nation's renewable resources. The Forest Service collects and publishes forest resource statistics through the Forest Inventory and Analysis (FIA) program. In support of the 2020 RPA Assessment, a recent publication, *Forest Resources of the United States, 2017*, provides forest resource statistics. FIA installed permanent plots across all forestland in the United States that are measured every 10 years, and the resulting data are used to generate estimates of forest area, volume, mortality, growth, removals, and timber-product output in various ways within the context of changes since 1953. Additional analyses look at the resource from an ecological, health, and productivity perspective. Users may obtain additional data using online tools at FIA. Pertinent highlights from the report include the following (Oswalt and others 2019):

- Forest and woodland area in the United States has plateaued at 823 million acres (333 million ha) following decades of expansion. Forest land area alone occupies 766 million acres (310 million ha). Together, forest and woodlands make up over one-third of the U.S. landscape and contain 1 trillion cubic feet (28.3 billion m^3) of wood volume.
- Although forest land is becoming more accessible to people and 67% of forest land is legally available for harvest activities, tree cutting and removal occurs on less than 2% of forest land per year. Contrast that with the nearly 3% disturbed annually by natural events such as insects, disease, and fire.
- Wildfire, insects, and disease are among the biggest threats to forests and woodlands in the nation. Low harvest rates, aging forests, mortality from insect and disease infestations, and extreme weather events have combined to create conditions that facilitate wildfire.
- Forest industry in the U.S. makes up 17% of global roundwood production, and the Nation has the highest intensity of industrial roundwood consumption per capita. The impact of the 2007 recession on wood product demand is still reflected in inventory data, with a 19% decline in Southern timber removals between 2006 and 2016.
- Bioenergy is an increasingly important industrial forest product. Wood energy accounts for 20% of all renewable energy and 41% of all domestic bioenergy in 2016. Most of the wood energy that was used was manufactured by the wood products industry. In fact, the United States accounts for 26% of total wood pellet production worldwide.
- Wood-processing facilities generated 4 million tons of mill residue in 2016, 99% of which was used for either fuel or fiber products such as pulp and paper.
- Tree removals for products, fire management, and land-use changes on National Forests are very low and consume only 0.2% of standing volume on average, annually.
- Despite the low volume of wood extracted from national forests, average annual net growth (calculated as gross growth minus mortality) declined while average annual mortality nearly doubled from 2006 to 2016. These patterns reflect aging forests and combinations of wildfire, drought, and insect infestations.

The Forest Service, through the national Research and Development office, also reports measures that relate to ecological, social, and economic dimensions of forest sustainability. The Montréal Process Criteria and Indicators, an internationally agreed upon set of sustainability measures, are used to organize this information. Individual reports for each of the Montréal Process's 64 indicators are provided, covering topics ranging from biodiversity conservation to forest fires to the many benefits derived from forests (USDA Forest Service 2021).

Forest Statistics and Measures

Forest Land Area and Ownership

In the United States, forest land area has been increasing since the 1930s. Figure 1–1 shows U.S. forest land from 1630 to 2017. Prior to 1900, a significant area of forest land was converted to agriculture and other uses. Since then, the area of forest land has increased. Forest land is defined as land that is at least 10% stocked by forest trees of any size, including lands that formerly had such cover and will be naturally or artificially reforested (USDA Forest Service 2020c). Notably, timberland (forest land that is producing or is capable of producing crops of industrial wood and not withdrawn from timber utilization by statute or administrative regulation (Oswalt and others 2019)) makes up 67% of the forest land, 87% of which is considered to be of natural origin. The remaining 13% would be considered planted forest, which may include plantations, augmented planting of natural stands, or planting for the purposes of restoration, such as after a fire (Oswalt and others 2019).

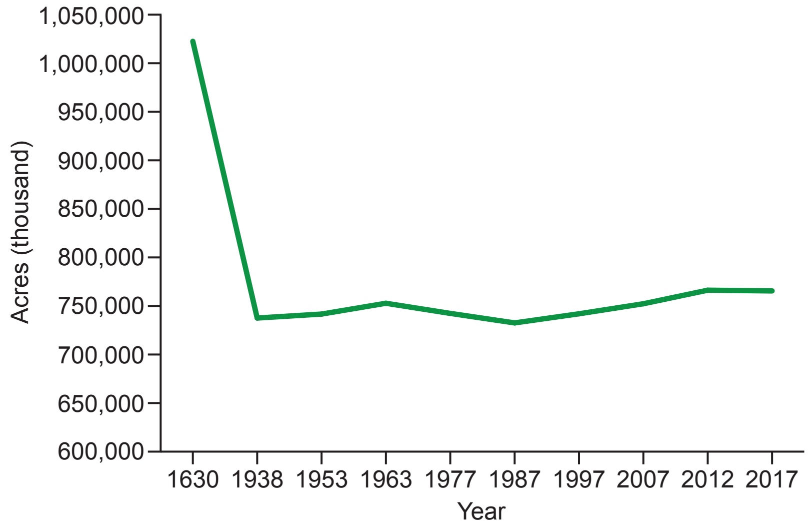

Figure 1–1. Forest land area in the United States, 1630–2017. (From Oswalt and others (2019).)

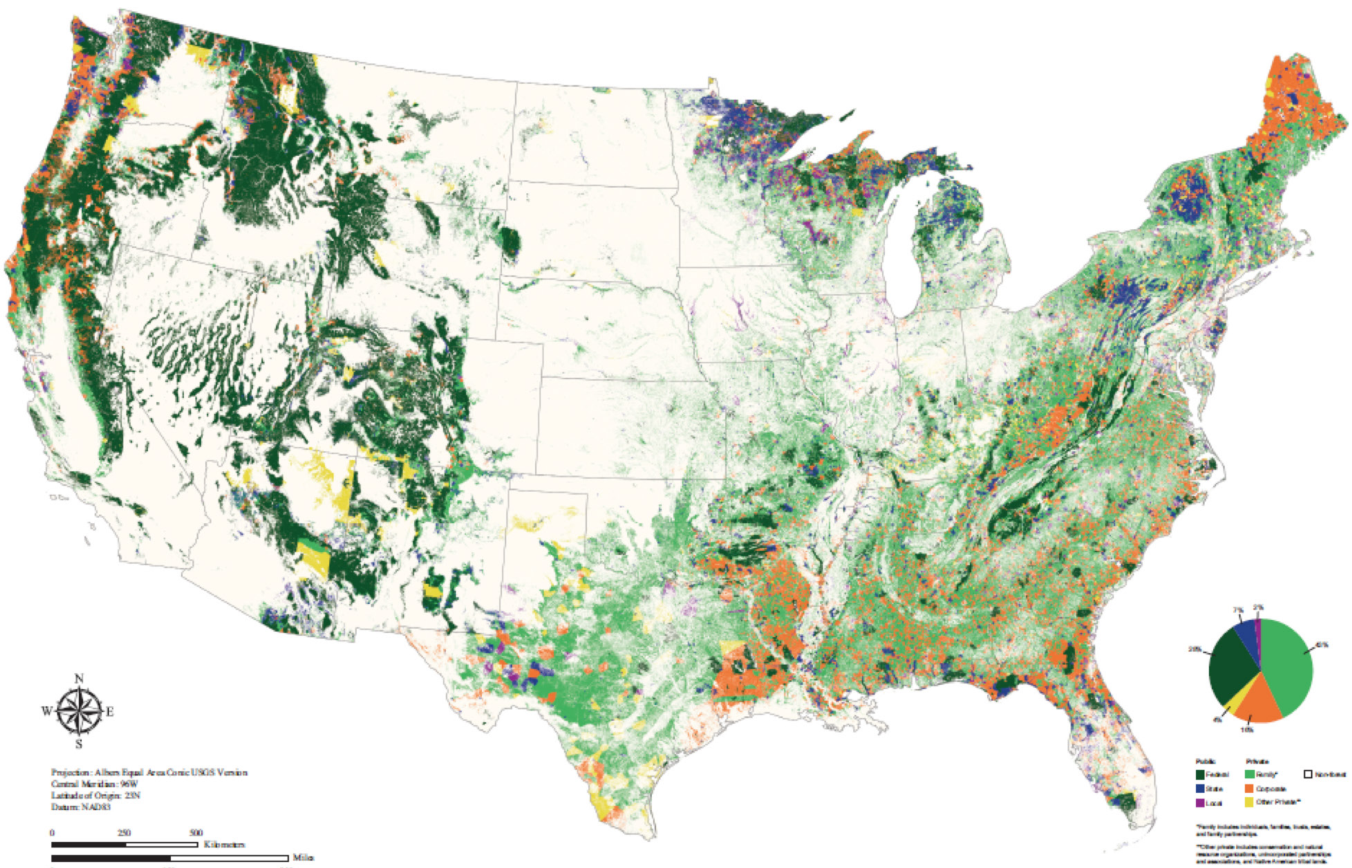

Figure 1–2. Distribution of forest and woodland by ownership category, 2014. (From Hewes and others (2014).)

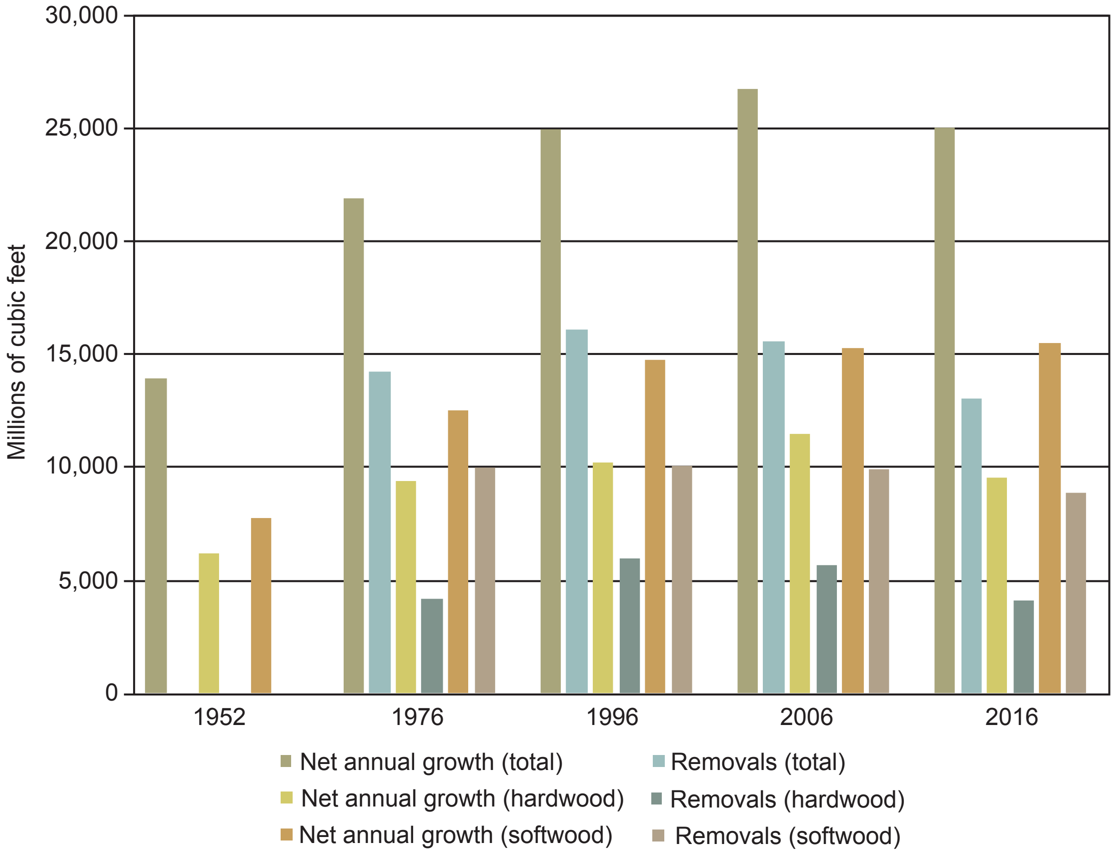

Figure 1–3. Net annual growth and removals for U.S. timberlands. (Data from Oswalt and others (2019).)

The highest percentage of planted timberland occurs in the southern forests, of which the primary forest-type group is loblolly–shortleaf pine, two species in the Southern Pine group.

Figure 1–2 highlights U.S. forest and woodland ownership patterns. Generally, private ownership is prevalent in the East, and public ownership is dominant in the West. Forty two percent of U.S. forest land is publicly owned, with the Federal Government controlling 31% of forest land overall. The Forest Service is the primary agency in this category, but many other agencies include the Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Department of Defense. State agencies control 9% of the Nation's forest and woodland, and local governments control an additional 2% (Oswalt and others 2019).

U.S. Annual Net Growth, Mortality, and Removals

FIA monitoring is used to assess the average volumes of growing stock of timber in the United States. Figure 1–3 shows average net annual growth of timber and removals, key measures of overall sustainability, for U.S. timberland ownership categories. Net annual growth is defined as gross growth minus mortality. Removals include the volume of growing-stock trees removed from the inventory during a specified year by harvesting operations such as timber stand improvement or land clearing. In the United States, net annual growth increased from 1952 to 2006 but has shown some slight decreases between 2006 and 2016. This is attributed to increased mortality from insect and disease infestations and forest fire, especially in the Rocky Mountain and Pacific Coast regions reported by FIA. Detailed information on annual net growth, mortality, and removals at a national, regional, and state level are reported by Oswalt and others (2019).

Forest Species Legality and Conservation Status

Various laws and organizations address conservation status of wood species that may be imported into the United States. The sustainable, ethically responsible, and legal use of wood products for various applications requires that their use does not affect threatened or endangered species. The Lacey Act was established in 1900 to ban trafficking of illegal wildlife and amended in 2008 to include plants and plant products such as timber and paper. Specifically, the Lacey Act makes it unlawful to import into the United States any plant or plant product that was illegally harvested. It also makes it unlawful to import certain products without a declaration. USDA Animal and Plant Health Inspection Service (APHIS), the National Marine Fisheries Service, and the U.S. Fish and Wildlife Service administer the Lacey Act (USDA APHIS 2020a).

The U.S. Endangered Species Act (ESA) of 1973 was established to conserve and protect U.S. endangered and threatened species and their habitats. It also serves as a method to meet U.S. responsibilities to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). CITES is an international agreement between governments to ensure that international trade of wild animals and plants does not threaten their survival. The USDA is responsible for enforcing regulations specific to the import and export of plants regulated by the ESA and CITES. Information about which wood species are covered by the ESA is available from the U.S. Fish and Wildlife Service, and those covered by CITES are in appendixes I and II of USDA APHIS (2020b).

Another essential source of information that should be consulted for imported wood species is the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species. Established in 1964, the IUCN is a comprehensive information source on the global conservation status of animal, fungi, and plant species. This tool is used to inform about biodiversity conservation policies and to provide information about range, population size, habitat and ecology, use and/or trade, and threats (IUCN 2020).

Forestry Accountability

An increased awareness of forest sustainability has become more important during the past decade. The public and industries that use wood products for building, consumer, and industrial products have created the need for understanding forest sustainability at new levels. Environmental, social, and economic considerations are critical components of forest management, ensuring that we have clean water, wildlife habitat, climate-resilient forests, and a supply of forest materials for producing wood products and energy. With these multiple uses, there has been increased awareness of how forests are managed to achieve long-term sustainable benefits. Several approaches are used to ensure sustainable supply of wood products, including federal, state, and local regulations, third party certifications, and an emerging ASTM standard.

USDA Forest Service

The mission of the USDA Forest Service is "to sustain the health, diversity, and productivity of the Nation's Forests and Grasslands to meet the needs for present and future generations." Managing over 193 million acres (78 million ha) of National Forests and Grasslands, the Forest Service is governed by multiple public laws and regulations that shape and govern all forest management decisions. (These include the Multiple Use Sustained Yield Act of 1960 (P.L. 86-517), Forest and Rangeland Renewable Resources Planning Act of 1973 (P.L. 93-378), National Forest Management Act of 1976 (P.L. 94-588), Healthy Forests Restoration Act of 2003 (P.L. 108-148), Agricultural Act of 2014 (P.L. 113-79), Agricultural Improvement Act of 2018 (P.L. 115-334), and Consolidated Appropriations Act of 2018 (P.L. 114-141), among others.) Although National Forests are managed to sustain multiple uses, over 95 million acres (38 million ha) are Wilderness and Roadless areas, designations that prohibit or limit timber harvest. To guide sustainable, integrated resource management, each National Forest has a Forest Land and Resource Management Plan (Forest Plan) that is developed and implemented collaboratively with state and local governments, local communities, Tribes, conservation groups, and other valued partners.

Forest management projects are planned and implemented on National Forests to advance sustainable ecological conditions and contribute to social and economic opportunities. Sustainable management activities may include the following examples:

- Reduction of forest fuels to reduce the risk of wildland fire
- Restoration of riparian areas to improve water retention, stream quality, and wildlife habitat
- Improvement of forest vegetation to encourage growth of native plants and grasses, shrubs, and forbs
- Improvement of vegetation conditions to restore ecosystem services
- Restoration of a vegetation community to a more desired natural state that is more resilient.

These activities are planned to improve forest health and may include timber management that provides roundwood logs or biomass for use in manufacturing wood products or producing renewable energy. Forest management actions on specific areas in the Forest Plan designated as suitable for timber production are highly reviewed under the National Environmental Policy Act (NEPA) (P.L. 91-190), in a public and transparent process.

Wood fiber sourced from a National Forest is consistent with sustainable land management practices as required per governing federal law and regulations.

Forest Certification Programs

Forest certification began more than 25 years ago. It emerged in the 1990s in response to market concerns about unsustainable forest management that was threatening forests, including illegal logging, and forest conversion to agriculture or other uses, primarily in developing countries. It is a process where an independent third party assesses the forest management program against a set of standards developed by a certification program. This approach is used to inform potential customers about forest sustainability of the fiber that was provided for use in various wood products. Currently, there are more than 50 certification schemes used around the world (FAO 2020).

Globally, the two largest forest certification programs, Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), released data reporting a combined total of 1.260 billion acres (510 million ha) of certified forest. However, after accounting for the double reporting, the total net certified forest land was 1.047 billion acres (424 million ha) (FAO 2019). It is reported that 11% of the world's forests are certified by these organizations.

In North America, five major certification systems are used:

- Sustainable Forestry Initiative (SFI)
- Forest Stewardship Council (FSC)
- American Tree Farm System (ATFS)
- Canadian Standards Association (CSA)
- Programme for the Endorsement of Forest Certification (PEFC)

The Sustainable Forestry Initiative (SFI) and the FSC are the largest certification programs in the United States. In the United States and Canada, the FSC program has 154.7 million certified acres (62.6 million ha), with approximately 253 unique forest management certificates (FSC 2019). SFI, which certifies forestlands in the United States and Canada, has grown from 90 million certified acres in 2004 to 375 million acres (from 36.4 million to 152 million ha) (SFI 2020a). The SFI program today has approximately 154 active unique forest management certificates (SFI 2020b), including 81 in the United States and 73 in Canada.

The growing trends in green building are helping drive sustainable forestry programs in the U.S. construction market. Builders and architects can use wood and paper products certified to the SFI, ATFS, CSA, FSC, and PEFC standards to achieve a point in the Certified Wood Pilot Alternative Compliance Path (ACP) under LEED 2009 and achieve a point in the Sourcing of Raw Materials Pilot ACP under LEED v4 (USGBC 2019). A second national system, Green Globes (GBI 2020), provides a green rating assessment, guidance, and certification program. It allows for one of two paths to gain points toward sustainable construction. The first is a performance path that requires a life-cycle analysis (LCA) using a recognized analysis tool; the second is a prescriptive path that may require recognized sustainably sourced materials as verified through third-party certification. These programs have created new opportunities to advance environmentally responsible forest management and help reduce the use of illegally sourced wood. However, it should be noted that these systems do not exclude wood from noncertified landowners.

Sustainable Forestry Initiative (SFI)

The SFI program was established by the American Forest and Paper Association in 1994 but today is an independent nonprofit organization. SFI currently certifies 375 million acres (151.7 million ha) in the United States and Canada. SFI has several standards to support the connection between forestry and forest products. This includes the Forest Management Standard, Chain-of-Custody (CoC), and Fiber Sourcing Standard. The Forest Management standard defines measures to protect forest lands and resources, whereas the CoC standard tracks fiber through harvesting to manufacturing and to the product. The Fiber Sourcing standard elevates procurement practices and environmental performance from forestland by documenting that the raw material comes from legal and responsible forests, whether they are certified or not. The SFI program also collaborates with the American Tree Farm System to increase forest certification on family forestlands (SFI 2020c).

Forest Stewardship Council (FSC)

Established in 1994, FSC is an independent, nongovernmental, nonprofit organization established to promote responsible management of the world's forests and is probably the most well-known forest certification program worldwide. Almost 543 million acres (220 million ha) of forest worldwide are certified to FSC standards and are distributed over 89 countries (FSC 2020). The FSC program includes two types of certifications. The Forest Management (FM) Certification applies FSC standards of responsible forestry to management of the forest land. A CoC certification ensures that forest products that carry the FSC label can be tracked back to the certified forest from which it came. More than 44,000 CoC certifications are in use by FSC members. The international and U.S. FSC websites have searchable databases of organizations that have FM or CoC certification, as well as the ability to locate FSC-certified products.

American Tree Farm System (ATFS)

The American Tree Farm System, a program of the American Forest Foundation (AFF), is the oldest of forest certification programs and was established in 1941. The ATFS focuses its program on private family forest landowners in the United States. Currently, ATFS has certified 19 million acres (7.7 million ha) of privately owned forestland and 74,000 family forest owners in 46 states. ATFS has established standards and guidelines for property owners to meet to become a Certified Tree Farm or Family Forest. The ATFS program is internationally recognized by the Programme for the Endorsement of Forest Certification (PEFC), with standards revised every 5 years. The AFF 2015-2020 Standards of Sustainability for Forest Certification (Standards) promote the health and sustainability of America's family forests. These Standards are designed as a tool to help woodland owners be effective stewards of the land as they adaptively manage renewable resources; promote environmental, economic, and social benefits; and work to increase public understanding of sustainable forestry. The Standards are based on international sustainability metrics and North American guidelines for sustainable forest management and serve as the basis for the American Tree Farm System® (ATFS) certification program (AFF 2020). Various options for owners include state, group, or individual certification. ATFS standards were designed for small woodland owners who would develop and implement a management plan, protect special sites, conduct self-monitoring, and combat invasive species.

Canadian Standards Association (CSA)

The Canadian Standards Association is a nonprofit organization and has developed more than 2,000 different standards for a variety of industries. The CSA first published Canada's National Standard for Sustainable Forest Management (SFM) CAN/CSA-Z809 in 1996 (CSA 2020). It was most recently updated in 2016. The SFM program includes the SFM Standard and a CoC standard. For lands to be certified to the CSA SFM standard, forest managers must follow the six criteria developed by the Canadian Council of Forest Ministers as part of an international process to create global criteria and indicators for sustainable forest management. Nearly 98.8 million acres (40 million ha) of Canadian forests were third-party certified to CSA in 2014; however, this dropped to nearly 32 million acres (12.9 million ha) in 2019 as other certification programs increased (Forest Products Association of Canada 2020). The CAN/CSA Z809 SFM Standard is endorsed by PEFC, the world's largest forest certification organization. This endorsement verifies that it meets a common, internationally accepted performance level, and was developed in a multi-stakeholder process.

Programme for the Endorsement of Forest Certification (PEFC) Schemes

The multitude of certification programs with competing standards and claims has made it difficult for land managers, members of the wood industry, and consumers to determine which certification program fits their needs (Fernholz and others 2004). The PEFC scheme was developed to address this issue and serves as an umbrella endorsement system that provides international recognition for national forest certification programs. Founded in 1999, the nonprofit, nongovernment PEFC is a leading global alliance of national forest certification systems. It represents most of the world's certified forest programs and the production of millions of tons of certified timber. The SFI, ATFS, and CSA programs have received official PEFC endorsement. PEFC has over 778 million acres (315 million ha) of certified forest, making it the largest forest certification system in the world. More than 20,000 companies have obtained PEFC chain-of-custody certification (PEFC 2020).

ASTM Standard Practice

ASTM Standard D7612-10 (reapproved 2015) (ASTM 2015), "Categorizing Wood and Wood-Based Products According to the Fiber Sources," is an alternate practice that sets minimum criteria and evaluation requirements for products employing the use of different systems to trace wood fiber to sources operating under different forest management or forest certification systems (ASTM 2015). It is being used by wood products manufacturers, distributors and retailers to provide consumers with information about how the wood fiber used to produce products conforms to various systems within specific forest management or forest certification systems. The three categories (ASTM 2015) under this standard include the following:

1. **Legal**—Fiber is from jurisdictions with a low risk of illegal activity or from controlled wood standards, stair-step standards, legality assessments, or other proprietary standards; the fiber procurement system governance is public legislative or regulatory processes or proprietary standards; documentation includes traceability to the applicable jurisdiction.
2. **Responsible**—Fiber is from jurisdictions with a low risk of illegal activity or from controlled wood standards, stair-step standards, legality assessments, or other proprietary standards; the fiber procurement system governance is public legislative or regulatory processes or proprietary standards or consensus based; content requires compliance with best management practices (BMPs) to protect water quality and ensures all fiber comes from known and legal sources or provides for

forest management plans in substantial compliance with relevant portions of Guide D7480-08 or equivalent; documentation includes traceability to the applicable jurisdiction or by a certified procurement system or by a chain-of-custody system.

3. **Certified**—Fiber is from jurisdictions with a low risk of illegal activity or from controlled wood standards, stair-step standards, legality assessments, or other proprietary standards; content provides for Forest Management Plans in substantial compliance with relevant portions of Guide D7480-08 or equivalent; the fiber procurement system governance is consensus based; documentation includes traceability by a chain of custody system.

Wood as a Green Building Material

Building construction consumes vast amounts of resources globally, which results in substantial environmental consequences. There is huge pressure to reduce the carbon footprint for construction activities especially for buildings. Wood, concrete, and steel are the main building materials. Of the three, wood construction acts as a greenhouse gas (GHG) emission reduction strategy and comes from a renewable and sustainable source. Many countries, including the United States, Canada, Japan, and Scandinavian countries, have used wood for centuries for construction. Wood is a unique, desirable, and ubiquitous material used for many things besides construction, including for energy and food (Skog and others 2015, Jakes and others 2016). Unlike competing materials, wood can be harvested sustainably with active forest management as it is done in the United States where forest stocks have been increasing over the past decades (FAO 2015, Sahoo and others 2019, Oswalt and others 2019). These three competing materials, especially wood, have developed environmental aspects based on surveying their respective industries. For wood construction products, documenting and publishing these aspects contribute to the future competitiveness by maintaining market access along with countering green-washing—the act of wrongly asserting environmental impact data when selling a product or service (Ritter and others 2011; Bergman and Taylor 2011). Life-cycle analysis is one such scientific tool that fights green-washing through development of environmental labels such as environmental product declarations (EPDs).

Life-Cycle Analysis

Life-cycle assessment (LCA) is a well-established internationally accepted method to quantify the environmental impacts of products, processes, and services, especially building products. Following international standards like ISO 14040 and 14044 (ISO 2006a,b), these analyses can cover the life of a product from extraction of raw materials to product production point ("cradle-to-gate") or through product delivery, construction, use, and final disposal point ("cradle-to-grave") (Fig. 1–4).

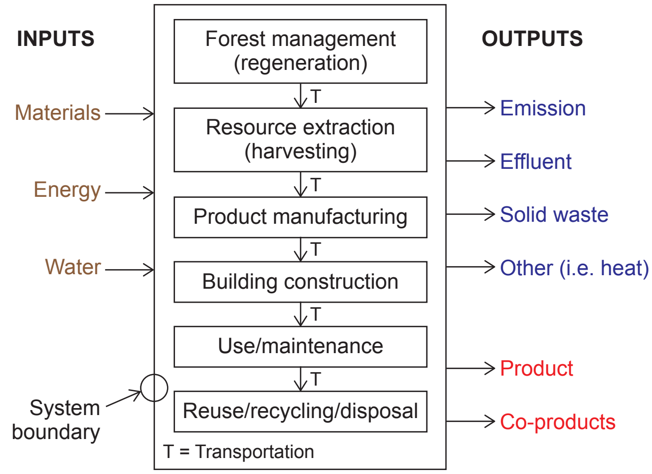

Figure 1–4. Whole life cycle from regeneration of trees to disposal of wood materials. (From Bergman and others (2014a).)

LCAs are composed of four stages (phases) as defined by the International Organization of Standardization (ISO): (1) goal and scope definition, (2) life-cycle inventory (LCI) analysis, (3) life-cycle impact assessment (LCIA), and (4) interpretation. A LCA study includes all stages, but an LCI study does not include stage 3. The goal and scope set out the framework of the study and explain how and to whom results are to be communicated. An LCI, a data- and time-intensive activity, measures all raw material and energy inputs and environmental outputs to manufacture a specific product, process, or service on a per-unit basis within well-defined system boundaries. For wood products, mill surveys are the main instrument to collect these data along with site visits. Many earlier life-cycle analyses were simply LCI studies, not LCA studies, and therefore did not include the LCIA phase. LCI results, referred to as flows, list the emissions to air and water such as fossil CO_2 and suspended solids along with the raw materials such as wood consumed during product production. LCIAs, as part of an LCA study, use these LCI flows to explore impacts for four areas: human health, resource depletion, social health, and ecosystem function. In the interpretation stage, alternatives for action to lower impacts are systematically evaluated (ISO 2006a,b). These LCIs and LCAs are often referred to as attributional because they focus on current year net emissions for a given product or service instead of consequential, where a what-if scenario is assessed (Bergman and others 2014b, Nepal and others 2016).

For conducting U.S. wood product LCIs and LCAs, USDA Forest Service Research and Development has been collaborating with the Consortium for Research on Renewable Industrial Materials (CORRIM, www.corrim.org). CORRIM is the premier LCA organization

Table 1–1. Environmental performance indexes for residential construction[a]

	Wood frame	Nonwood frame	Difference	Change[b] (%)
Minneapolis design[c]				
Embodied energy (GJ)	651	764	113	–17
Global warming impact (CO_2 kg)	37,047	46,826	9,779	–26
Air emission index (index scale)	8,556	9,729	1,173	–14
Water emission index (index scale)	17	70	53	–312
Solid waste (total kg)	13,766	13641	–125	1
Atlanta design[d]				
Embodied energy (GJ)	398	461	63	–16
Global warming impact (CO_2 kg)	21,367	28,004	6,637	–31
Air emission index (index scale)	4,893	6,007	1,114	–23
Water emission index (index scale)	7	7	0	0
Solid waste (total kg)	7,442	11,269	3,827	–51

[a] Lippke and others (2004).
[b] Percentage change = [(Wood frame – Nonwood frame)/(Wood frame)] × 100.
[c] Steel frame.
[d] Concrete frame.

for wood products in the United States and has a huge reservoir of forestry and forest products LCIs and LCAs (Boyd and others 1976; CORRIM 2005, 2010, 2017). These consistently show that many wood-based materials use less fossil fuels to produce than competing materials (Puettmann and Wilson 2005, Puettmann and others 2010, Bergman and others 2014b). Using wood products can also lower atmospheric carbon dioxide levels because growing forests capture carbon and harvested wood products store the accumulated carbon while in use and when disposed of at end of life, in landfills (Lippke and others 2011, 2019; Bergman and others 2014b). In addition, most of these LCAs were conducted on structural wood products in which the underlying LCI data were incorporated into on-demand whole-building LCA software tools such as the Athena Impact Estimator for Buildings (EI4B) and Tally. ASTM (2016) standard practice was created so whole-building software developers are providing tools with a consistent framework and users can understand what goes into these tools. Specifically, this practice lists criteria that building designers need to consider when comparing the life-cycle environmental impacts associated with a reference building design and a final building design, including additions to current buildings, where applicable.

Table 1–1 shows the environmental performance indexes on residential construction based on the CORRIM (2005) seminal research and reported by Lippke and others (2004). The results using the Athena IE4B show comparisons for two wood and nonwood residential housing designs on their structural elements at two different locations (Minneapolis, Minnesota (steel) and Atlanta, Georgia (concrete)). For most indexes, there are notable advantages for wood over the nonwood designs. For example, the global warming impact for wood shows a percentage change of –26% and –31% compared to steel and concrete, respectively.

The marketplace has an increasing need for credible and transparent product eco-labels based on LCA data, especially for international trade and for green building construction certification. Over the past decade, stakeholders in the U.S. wood products industry have been creating many such eco-labels under the ISO standard of LCA-based EPDs (ISO 2006c).

Environmental Labeling

Because environmental labeling or eco-labels are intended for public sharing by organizations, credible and transparent environmental labeling of products must be based on sound science (such as LCA). Many eco-labels exist but the premier ones are based on science such as EPDs. Unlike type I and II declarations, EPDs are a type III declaration using underlying LCA data to develop the summary of environmental impacts associated with product manufacturing, much like a nutritional label for food (ISO 2006c). Following the same framework called a product category rule (PCR), a third-party verified EPD is drafted so it can be used for product comparison (Bergman and Taylor 2011, ISO 2017). EPDs describe standardized LCA data in a way that is meaningful to people unfamiliar with LCA to facilitate their understanding.

The need for credible and transparent life-cycle environmental product information continues to increase globally. LCA-based EPDs have met this requirement and are becoming the globally preferred instrument for environmental impact information on products.

LCA data provide the background information for producing EPDs. The use of product-specific data is preferable to generic data, as an EPD is only as credible as the LCA data it uses. Therefore, developing, maintaining, and updating LCA data for products on a five-year cycle require consistent effort and funding to ensure freshness of wood EPDs (Bergman and Taylor 2011, Oneil and others 2017). By acting as leaders in embracing the EPD movement, the U.S. forest products industry has demonstrated good corporate environmental citizenship. EPDs are progressive,

Table 1–2. Partial data from an environmental product declaration for North American softwood lumber, per m^3 (AWC/CWC 2020)

Impact category indicator	Unit	Total	Forestry operations (A1)	Transport to facility (A2)	Manufacturing (A3)
GWP[a]	kg CO_2 eq.	63.12	–2042.32	10.01	2095.43
GWP[b]	kg CO_2 eq.	63.12	10.55	10.01	42.56
ODP[c]	kg CFC-11 eq.	2.82×10^{-6}	1.10×10^{-7}	1.00×10^{-8}	2.70×10^{-6}
AP[d]	kg SO_2 eq.	0.52	0.14	0.08	0.30
EP[e]	kg N eq.	0.26	0.02	0.01	0.23
POCP[f]	kg O_3 eq.	13.68	4.43	2.14	7.11
ADPf[g]	MJ, NCV	833.37	141.22	136.57	555.58
FFD[h]	MJ surplus	101.51	21.58	19.79	60.14

[a] Global warming potential (with biogenic CO_2).
[b] Global warming potential.
[c] Depletion potential of the stratospheric ozone layer.
[d] Acidification potential of soil and water sources.
[e] Eutrophication potential.
[f] Formation potential of tropospheric ozone.
[g] Abiotic depletion potential (ADP fossil) for fossil resources.
[h] Fossil depletion potential.

fully transparent environmental statements—the entities developing and using them are viewed as sustainability leaders. EPD development is an ongoing activity. A side-benefit of having constantly updated LCA data is that the U.S. forest products industry can document the benefits of carbon storage in durable wood products.

Table 1–2 illustrates partial life-cycle information from a wood product EPD. EPDs can use data from cradle-to-gate or cradle-to-grave, depending on the project scope. Most EPDs are business-to-business (B2B: cradle-to-gate) instead of business-to-consumer (B2C: cradle-to-grave). These data based on a cradle-to-gate LCA analysis were drawn from table 8 of the North American softwood lumber B2B EPD, second edition (AWC/CWC 2020). This EPD follows the framework from the 3rd edition of the PCR for North American Structural and Architectural Wood Products (UL 2019) and Part A: Life Cycle Assessment Calculations Rules and Report Requirements (UL 2018). Other results required by the PCR but not included in Table 1–2 are total primary energy consumption, material resources consumption, and solid waste.

EPDs are just one form of environmental labeling using LCA as the science to support their reporting. There is a similar approach for whole buildings referred to as environmental building declarations (EBDs). EBDs conducted in conformance with the European standard EN 15978 (CEN 2011) summarize the embodied and operational environmental impacts over the full building life cycle. The drive to develop EBDs is similar to that for EPDs, by acquiring green building certification points for specific activities along with educational and marketing uses. Gu and Bergman (2018) and Woodworks (2017) reported on a whole-building LCA and EBD conducted on the University of Massachusetts–Amherst mass timber Olver Design Building. Gu and Bergman (2018) focused more on the whole-building LCA and subsequent EBD, whereas Woodworks (2017) focused mostly on the planning, design, and construction of the building along with the approval process. The introduction of a new mass timber product, cross-laminated timber (CLT), in the United States has allowed for greater utilization of wood in nonresidential buildings (Anderson and others 2020). The 2021 International Building Code will support three new types of construction (Types IV-A, IV-B, and IV-C) and allow mass timber buildings of taller heights, more stories above grade, and greater allowable areas compared to existing provisions for heavy timber buildings (ICC 2020).

Carbon Impacts

There is a global push for materials that have a low carbon footprint (CFP) to conserve our energy resources and avoid GHG emissions. By measuring all the direct and indirect energy and material inputs to the manufacturing of a product and quantifying the GHG emissions per unit of product, the CFP of a product can be calculated (ISO 2018; Negro and Bergman 2019). Therefore, a CFP is the outcome of an LCA limited to emissions that have an impact on climate change. Tracking carbon throughout its whole life cycle requires a comprehensive and detailed perspective because carbon flows for forests and associated harvested wood products are complex. Figure 1–5 illustrates the utilization of wood resources by the U.S forest products and associated industries for the many wood products manufactured.

During the manufacturing of wood products, energy is used during harvesting to run equipment such as chainsaws, feller bunchers, and skidders, to fuel log transport to mills, and during production to power saws, planers, dryers, and other equipment. Energy consumed during the manufacturing of fertilizers, pesticides, and herbicides used during tree planting also needs to be accounted for. Depending on the energy source, the released emissions contribute to an assortment of impact categories such as acidification (such as sulfur emissions), eutrophication (nitrogen), smog

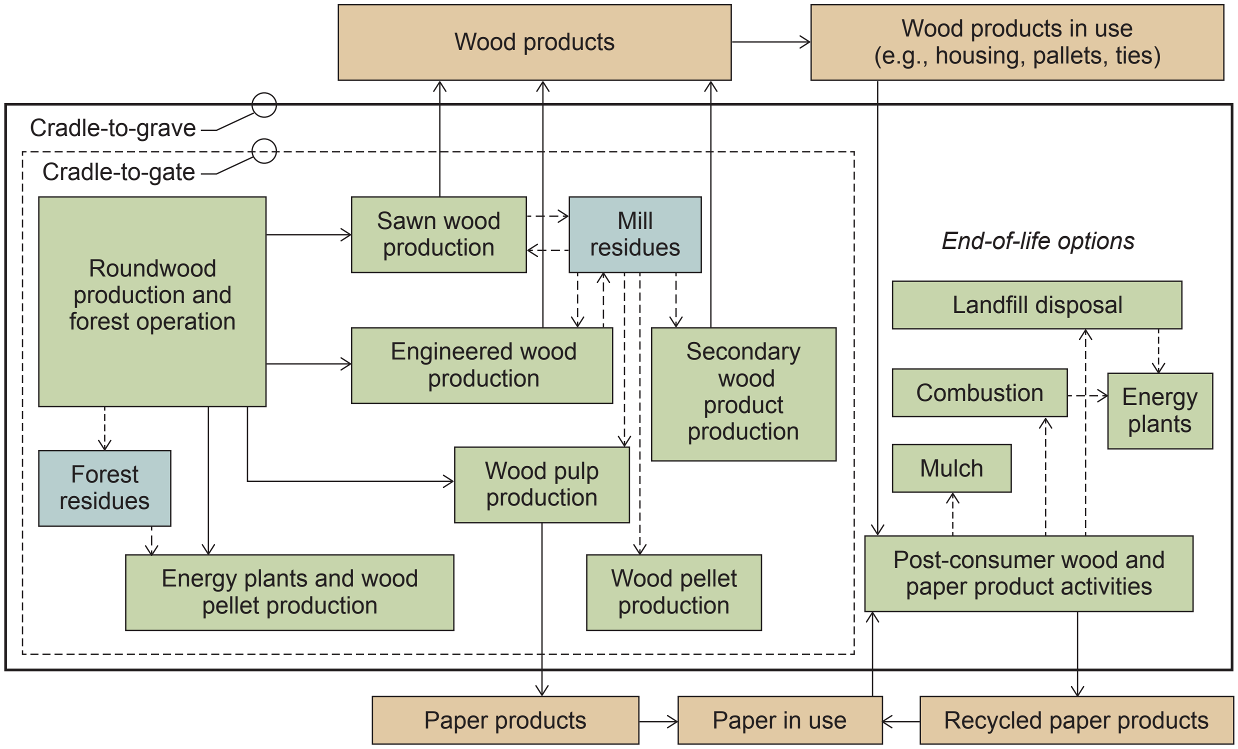

Figure 1–5. Broad view of harvested wood product carbon flow. (From Bergman and others (2014b) and Bais-Moleman and others (2018).)

(particulates), and global warming (CO_2). Whereas many gases (such as methane) contribute to global warming and CFP, CO_2 is by far the most significant GHG in wood product life cycles from forest cradle to mill output gate (Puettmann and Wilson 2005, Puettmann and others 2010).

There are several ways that the carbon impacts of wood products are assessed through biogenic carbon emissions, carbon storage, and avoided emissions (Bergman and others 2014b). Biogenic CO_2 is emitted from burning biomass. Carbon storage occurs when wood in solid form is placed in service (or in landfill). Avoided emissions are emission reductions for a given product that occur outside a product's life cycle when it is used instead of a comparable alternative.

Biogenic Carbon

Energy production from combustion results in CO_2 emissions. When natural gas, coal, oil, or wood are burned, CO_2 and water vapor are the main atmospheric emissions. The associated energy may be used indirectly, such as sources for electricity generation that can be used to power electric saw motors or directly in the production process for heat or steam for wood dryers. For fossil fuels (coal, petroleum, and natural gas), the CO_2 emissions are commonly classified as fossil CO_2. This classification contrasts with biogenic CO_2, which is emitted from the burning of biomass (such as wood). In the case of wood products, much of the process energy for manufacturing facilities is provided from burning wood-processing (mill) residues (Puettmann and Wilson 2005, Puettmann et al. 2010), thus mainly releasing biogenic CO_2.

In terms of the contribution of CO_2 to the greenhouse effect and the impact to climate change, there is no difference between the atmospheric physics and chemistry of fossil and biogenic CO_2. However, a distinction is commonly made between biogenic and fossil energy sources in life-cycle-based analyses because of the natural cycling of biogenic CO_2 from the atmosphere into wood resources (and other living materials) and back to the atmosphere in comparison with the one-way flow of fossil CO_2 to the atmosphere (Fig. 1–6). Bergman (2012) and Salazar and Bergman (2014) showed how the dynamic timing of GHG emissions for long-lived wood products and their impact to climate change using the time-zero equivalent method resulted in greater precision than the current global warming potential (GWP) metric while using the same reporting unit, kg CO2eq. This approach is important when considering carbon fluxes over a period of time (Fig. 1–7).

Carbon Storage

For a carbon storage frame of reference, in the United States, where the vast majority (~90%) of residential housing is framed with wood, an average single-family house of 233 m^2 in 2012 contains roughly 22,000 oven-dried kilograms of structural wood components (Meil and others 2004, McKeever and Elling 2015, Elling and McKeever

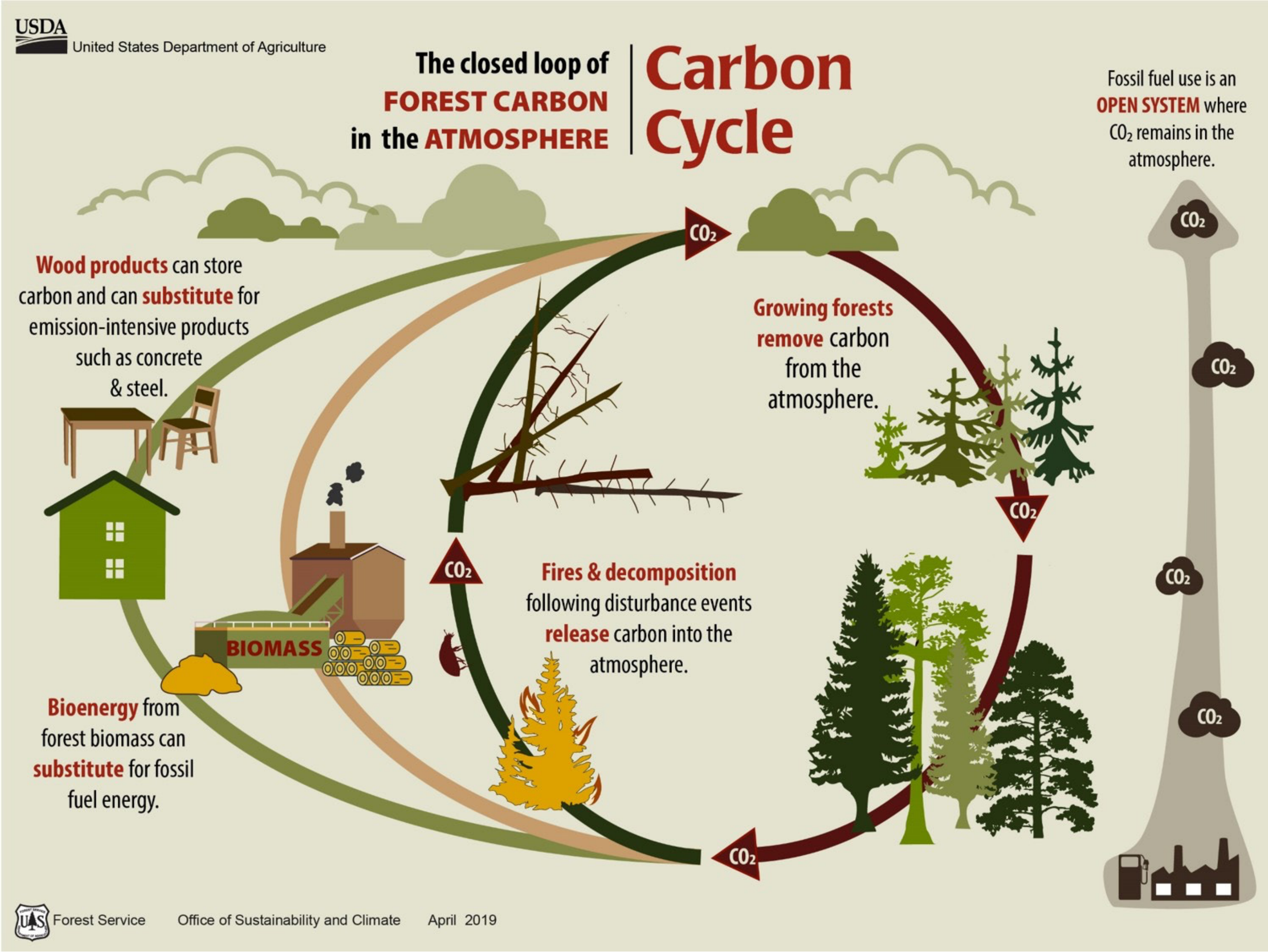

Figure 1–6. Carbon cycle.

2018, USCB 2020a). Therefore, a 233-m^2 home could store 11,000 kg, or about 50 kg/m^2 of carbon assuming wood carbon content at 50% and excluding adhesives (Negro and Bergman 2019). If we considered single-family housing at roughly 86 million units in the United States for 2017, the current carbon stored is 850 million metric tonnes of carbon (USCB 2020b). This value likely underestimates the total carbon stored in buildings in the United States because of the many other nonstructural wood building products used and the millions of multifamily housing units previously constructed that were not accounted for. Service life of structural wood products tends to track the service life of the structure itself. Therefore, given a median life of 80 years for a single-family home (Skog 2008), the stored carbon can last from two to three forest rotation cycles of intensely managed, highly productive forests (O'Connor 2004, Smith and others 2006.

Carbon in wood products may continue to be stored after its service life in a building, or it may be emitted by burning or decay. Wood products may end up in landfills where most of the wood does not decompose, it may be recycled into new engineered products, it may be burned for its energy while avoiding fossil fuel combustion, or it may be reused as is in new construction (Skog 2008, Bergman and others 2013).

Avoided Emissions

Use of wood products can help to reduce contributions to the atmosphere that increase the greenhouse effect. Avoided GHG emissions are the cumulative GHG emission savings resulting from the use of a product, compared to its alternative along the supply chain. To find the avoided emissions for a given product, GHG emissions are estimated for the production of the in-use equivalent amounts of the two products. Bergman and others (2014b) reported that, on average, the use of a wood building product instead of its alternative avoids the use of about four times as much fossil fuel as the cradle-to-gate manufacture of the wood product requires. The reduced carbon emission impacts associated with woody biofuel use and storage of carbon in long-lived wood products result in lower net carbon emissions of wood products compared to nonwood product alternatives. The combined emissions reductions due to biofuel usage, carbon storage, and avoided fossil emissions are always greater

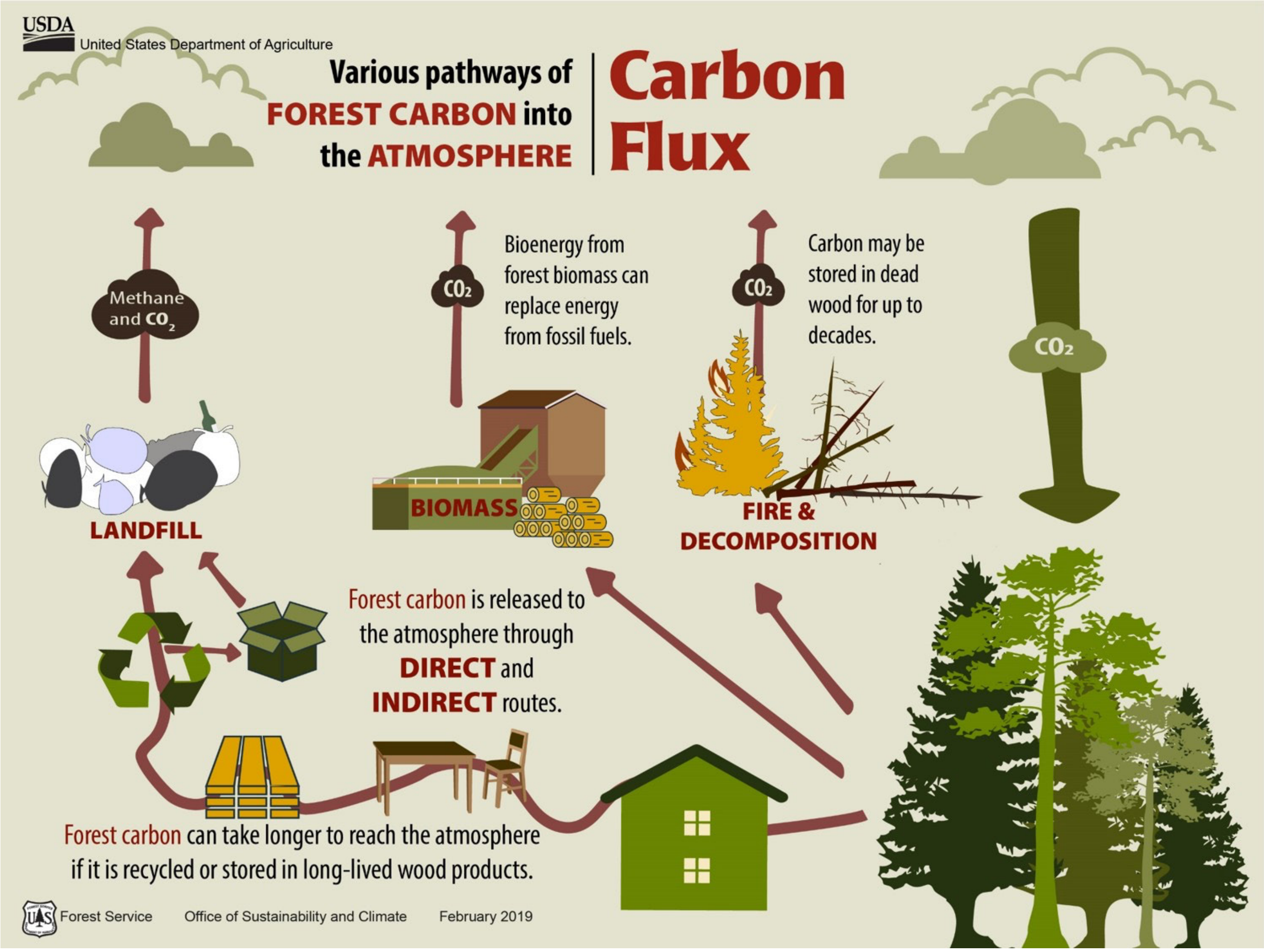

Figure 1–7. Carbon flux.

than the wood product manufacturing carbon emissions (Bergman and others 2014b). Nepal and others (2016), using a consequential life-cycle analysis approach, suggest strategies for increased use of traditional wood in place of nonwood structural products in nonresidential construction buildings, which would be effective in mitigating CO_2 emissions. Increasingly, mass timber buildings are being constructed in the mid- to high-rise category, which has been dominated by concrete and steel construction. The recent update of the International Building Codes for 2021 introduced new types of mass timber construction up to 18 stories (ICC 2020). In conjunction, several U.S. studies have been initiated to investigate the environmental, economic, and forest management impacts of mass timber manufacturing and construction, including Kelley and Bergman (2017) and Gu and Wishnie (2020), with recent results showing both positive life-cycle environmental and regional economic impacts while detailing approaches to improving the life-cycle costs for multiple story mass timber buildings (Liang and others 2019, 2020; Scouse and others 2020; Chen and others 2020; Lan and others 2020; Gu and others 2020).

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Wood Handbook

Wood as an Engineering Material

Forest Products Laboratory | United States Department of Agriculture Forest Service | Madison, Wisconsin

Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

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Pesticide Precautionary Statement

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

Caution: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife, if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.