9 Forests

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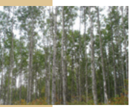


KEY FINDINGS

1. Net uptake of 217 teragrams of carbon (Tg C) per year by the forest sector in North America is well documented and has persisted at about this level over the last decade. The strength of net carbon uptake varies regionally, with about 80% of the North American forest carbon sink occurring within the United States (*high confidence, very likely*).

2. Forest regrowth following historical clearing plays a substantial role in determining the size of the forest carbon sink, but studies also suggest sizeable contributions from growth enhancements such as carbon dioxide fertilization, nitrogen deposition, or climate trends supporting accelerated growth (*medium confidence*). Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.

3. Annual harvest removals from forestry operations in select regions decrease forest carbon stocks, but this decline in stocks is balanced by post-harvest recovery and regrowth in forestlands that were harvested in prior years. Removal, processing, and use of harvested biomass causes carbon emissions outside of forests, offsetting a substantial portion (about half) of the net carbon sink in North American forests (*high confidence*).

4. Recent trends in some disturbance rates (e.g., wildfires and insects) have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions reduced sink strength across the continent by 11 Tg C per year, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation (*medium confidence*).

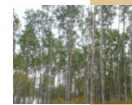
5. Several factors driving the carbon sink in North American forests are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake (*medium confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

9.1 Introduction

The forest land area of North America increased from an estimated 719 million hectares (ha) in 2005 to more than 723 million ha in 2015 and now represents 36% of the land area in North America and 18% of the world's forest land area (FAO 2016b). The increase in forest land area over the last decade was driven entirely by gains in the United States, while Canada and Mexico both lost forestland (see Table 9.1, p. 367). The area of other wooded lands also increased in North America over the last decade, with substantial gains in the United States, no change in Canada, and loss in Mexico.

Forest ecosystems are the largest terrestrial carbon sink on Earth, and their management has been recognized as a relatively cost-effective strategy for offsetting greenhouse gas (GHG) emissions (Canadell and Schulze 2014). In North America, forests—including urban forests, woodlands, and the products obtained from them—play a major role in the carbon cycle (Goodale et al., 2002). Since this report includes forestland from Canada, Mexico, and the United States, forestland is defined according to the Global Forest Resource Assessments from the United Nations Food and Agricultural Organization (FAO 2010, 2016b). This definition also is widely used for land representation in GHG reporting to the United Nations Framework Convention on Climate Change (UNFCCC; see U.S. EPA 2018) to ensure consistency and comparability in national reporting. Forest area is defined as land spanning greater than 0.5 ha with trees higher than 5 m and canopy cover of more than 10%, or trees able to reach these thresholds *in situ*. Other wooded lands are



defined as land not classified as forest, spanning greater than 0.5 ha with 1) trees higher than 5 m and a canopy cover of 5% to 10%; 2) trees able to reach these thresholds *in situ*; or 3) land with a combined cover of shrubs, bushes, and trees above 10%. Forests and other wooded land do not include land predominantly used for agriculture or urban purposes (FAO 2010). For this reason, urban forests are not included in this chapter, but their contribution to total carbon stocks and stock changes is described.

Forests' capacity to uptake and store carbon is influenced by many socioeconomic and biophysical factors (Caspersen et al., 2000; Joos et al., 2002; Birdsey et al., 2006; Zhang et al., 2012). Sustained investment in afforestation, reforestation, and improved forest management is an option for elevating the role forests play in future climate mitigation. This chapter presents the most recent estimates of carbon stocks and stock changes across the continuum of land with trees in North America and highlights advances in forest carbon cycle science since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007).

9.2 Historical Context

Forestland, and thus forest carbon, has changed substantially in North America over the last several hundred years. In the United States, for example, forestland amounts to an estimated 72% of the area that was forested in 1630, with roughly 120 million ha converted to other uses (mainly agricultural) primarily from 1850 to 1910 (Smith et al., 2009). National assessments of forest land area and carbon dynamics have been conducted in Canada, Mexico, and the United States, but the motivation for these reports and the methods and data sources they use differ substantially among countries. In recent decades, official government estimates of forest land area, forest carbon stocks, and stock changes have been compiled following guidelines from the Intergovernmental Panel on Climate Change (IPCC 2003, 2006). However, the methods for estimating carbon stocks and their changes (e.g., stock difference versus gain-loss) still differ based on country-specific circumstances, but estimation approaches have evolved as new and better information has become available in each country. Of the numerous key findings SOCCR1 identified on the

Table 9.1. Estimated Area (in Thousands of Hectares) of Forest and Other Wooded Land in North America in 2005 and 2015

Country[a]	Forestland[b]		Other Wooded Land[c]	
	2005	2015	2005	2015
Canada	347,576	347,069	40,866	40,866
Mexico	67,083	66,040	20,378	19,715
United States	304,757	310,095	15,452	21,279
Total[d]	719,416****	723,204****	76,696****	81,860****

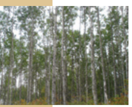
Notes

a) Estimates based on FAO (2016b).

b) Defined as land spanning greater than 0.5 hectare (ha) with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds *in situ* (FAO 2010).

c) Defined as land not classified as forest, spanning greater than 0.5 ha with trees higher than 5 m and a canopy cover of 5% to 10%; or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes, and trees above 10% (FAO 2010).

d) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.



role of forests in the North American carbon cycle, many (e.g., land-use change) continue to be relevant 10 years later, along with several emerging topics (e.g., climate feedbacks).

9.3 Current Understanding of Carbon Fluxes and Stocks

9.3.1 Carbon Stocks and Pools

Forests

Carbon is continuously cycled among the atmosphere and ecosystem carbon storage pools (i.e., above- and belowground biomass, dead wood, litter, and soil). This cycling is driven by biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and allocate a portion of this carbon to growth, carbon is removed from the atmosphere and stored in living tree biomass. As live biomass dies, litter and dead wood are deposited on the forest floor and in the soil below ground (e.g., dead roots). The carbon in these dead components is either stored as soil organic matter or released to the atmosphere or water through decomposition by microorganisms. When forests are harvested, some of the biomass carbon is transferred to harvested wood products from which it may be lost to the atmosphere (burned) in the year of the harvest (e.g., fuelwood [including pellets] and mill residues) or stored for a few years (e.g., paper products) to centuries (e.g., sawnwood or panels used in buildings) (IPCC 2006; Skog 2008).

Carbon stocks in North American forests have continued to increase over the last decade to an estimated 103,110 teragrams of carbon (Tg C), of which 32% is in live biomass and 68% is in dead organic matter (see Table 9.2, this page; Stinson et al., 2011; Köhl et al., 2015; FAO 2010, 2016b; U.S. EPA 2018). The increase in total carbon stocks is largely due to increases in aboveground biomass in the eastern United States, even as carbon stocks in Canada decreased slightly in recent years because of natural disturbances such as insects and wildfire (Stinson et al., 2011; Köhl et al., 2015; FAO 2010, 2016b; U.S. EPA 2018; ECCC 2016).

Carbon density (i.e., the amount of carbon stored per unit of land area) is highly variable (e.g., see Figure 9.1, p. 369, for the distribution of aboveground live biomass density on forestland in North America). The estimated carbon density in North American forests is 142.4 megagrams of carbon (Mg C) per hectare. In Canada, the largest carbon densities are in boreal and cordilleran forests (ECCC 2016; Kurz et al., 2013). In the United States, forests of the Northeast, upper Midwest, Pacific Coast, and Alaska continue to store the most

Table 9.2. Forest Carbon Stocks (in Teragrams of Carbon) by Carbon Pool in North America

Country	Aboveground Biomass	Belowground Biomass	Dead Wood	Litter	Soil
Canada[a]	11,162	2,746	4,683	11,666	19,729
Mexico[b]	1,597	396	2	NA[c]	NA
United States[d]	14,182	2,923	2,570	2,680	28,774
Total[e]	26,941****	6,065****	7,255****	14,346****	48,503****

Notes

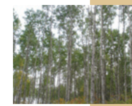
a) Estimates based on FAO (2010).

b) Estimates based on FAO (2016b).

c) Not applicable.

d) Estimates based on U.S. EPA (2018).

e) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.



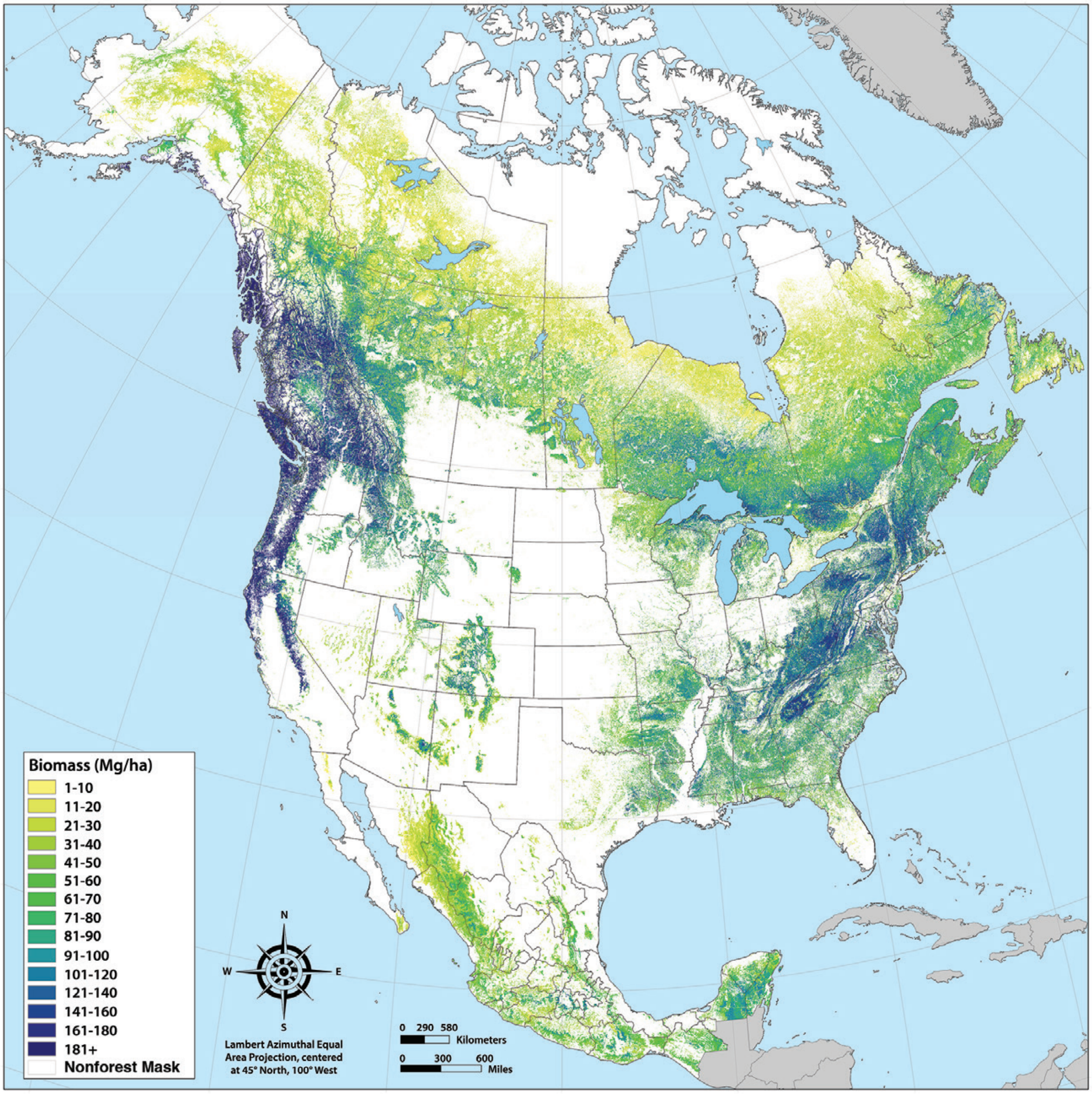
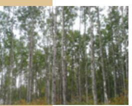


Figure 9.1. Hectares (ha) of Aboveground Forest Biomass Across North America. This comprehensive map combines four independently developed maps of biomass for Canada, Alaska, the conterminous United States, and Mexico (Beaudoin et al., 2014; Blackard et al., 2008; Wilson et al., 2013; MREDD+ Alliance 2013). A common legend, map projection, and spatial resolution of 250 m were applied to the individual maps with no attempt to harmonize the methods used for each of the original map products. Biomass of nonforest areas is masked by including only land-cover and land-use categories 1–6 from the North American Land Change Monitoring System (NALCMS 2018). Base years of the original maps are Canada, 2001; Alaska, 2004; conterminous United States, 2000–2009; and Mexico, 2007. [Figure source: Kevin McCullough, U.S. Forest Service. North American Biomass and Disturbance Mapping Working Group, 2014.]



carbon (U.S. EPA 2018; see Figure ES.1, p. 23, for a description of the areal extent of regions in the United States). In Mexico, forest carbon stocks are split fairly evenly among temperate, tropical, and semiarid forests (INECC/SEMARNAT 2015).

Woodlands

Woodlands are areas with tree coverage that falls between savanna and forest biomes. In the United States, for example, tree cover for woodlands does not meet the criteria for forestlands or agroforestry. Most woodlands occur in a matrix of grass vegetation and have been expanding in recent decades as trees and woody shrubs encroach on grasslands around the world, including in the western United States (Archer 1994; Briggs et al., 2002; Weisberg et al., 2007). For example, Asner et al. (2003) estimated a 10% increase in woody plant cover over a 40,000 ha area of northern Texas from 1937 to 1999 and an associated biomass carbon stock increase of 120 grams of carbon (g C) per m^2. In the Intermountain West, woodland areas increased by about 1.3 million ha from 2005 to 2010 and resulted in an estimated net carbon stock increase of 6,439 Mg in biomass, litter, and dead wood (Coulston et al., 2016; Ogle and Zeigler 2016). Woody encroachment also could affect soil carbon stocks (Hibbard et al., 2001), although this may not be the case in all woodland systems (Hughes et al., 2006) and may vary depending on the climate (Jackson et al., 2002).

9.3.2 Fluxes

North American forests currently act as a net sink for atmospheric carbon dioxide (CO_2; Hayes et al., 2012; King et al., 2015). A summary of data reported in recent GHG inventories (ECCC 2016; INECC/SEMARNAT 2015; U.S. EPA 2018) suggests that the North American carbon sink in forestland remaining forestland was about 325 Tg C per year over the last decade, with U.S. forests accounting for most of the sink (see Table 9.3, p. 371, and Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372, for an explanation of associated terms). This sink results from photosynthetic uptake that exceeds the releases of forest carbon by plant and heterotrophic respiration and from fire. A sizeable portion of the net uptake of atmospheric carbon within forestlands is offset by harvest-related emissions. These emissions include wood processing—from log removal to product generation—as well as the decay and combustion of harvested wood products, which together release about 124 Tg C per year. Thus, the net forest sector–atmosphere flux for North America is estimated to be a sink of 217 Tg C per year over roughly the last decade. Urban trees are estimated to uptake another 27 Tg C per year in the United States and Canada. Note that the fluxes reported here represent contemporary rates in recent years, spatially integrated to the country scale. Future legacies resulting from contemporary or historical drivers of forest carbon dynamics are not included. Such trends are particularly important if those drivers exhibit long-term trends, as in a decline or increase in harvest or natural disturbance rates, which would lead to trends in carbon fluxes.

Net forest carbon gain and loss constitute a source of 11 Tg C per year in North America. In the United States, net emissions from forest carbon losses encompass losses of aboveground biomass from conversion to croplands, grasslands, and settlements and include both prompt and residual legacy emissions from conversions that occurred over a 20-year time frame. Canada adopted a similar approach for quantifying emissions but accounted for conversions to croplands, settlements, and wetlands. The U.S. and Canadian estimated flux from forest carbon gains and losses includes all live biomass, dead organic matter, and soil carbon components.

Forests are generally believed to neither release nor absorb substantial quantities of methane (CH_4), though upland soils can act as modest sinks and forested wetlands can be CH_4 sources. However, forest fires release CH_4, contributing a 25-year global warming potential (GWP) of 9 Tg of CO_2 equivalent[1] (CO_2e) per year in Canada and releasing 0.22 Tg CH_4

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 25-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

Table 9.3. Net Emissions of Carbon Dioxide Equivalent (CO_2e)[a] for Forestlands from Net Forest Gain and Loss, Tree Growth in Urbanized Settlements, and Harvested Wood Products of Domestic Origin, by Country and Expressed in Teragrams of Carbon (Tg C) per Year

Tg C per Year	Canada[b]	United States[c]	Mexico[d]	Total[k]
1. Net Ecosystem Exchange for Forestland Remaining Forestland[e]	–18	–267	–41	–325****
Stock Change for Forestland Remaining Forestland[e] (Δ Forest C)	–27	154	ND[j]	127
2. Net Flux Due to Forest Area Gain and Loss ($A_{Loss} + A_{Gain}$)	3	0	9	11***
Emissions from Forest Area Loss[f] (A_{Loss})	3	23	12	38
Emissions from Forest Area Gain[g] (A_{Gain})	0	–23	–3	–27
3. Settlements Remaining Settlements[h] (Urban; Net Ecosystem $Production_{settled}$)	–3	–24	ND	–27***
4. Emissions from Biomass Removal and Use[i] (F_{HWP})	35	89	ND	124***
Harvest Removals of Forest Carbon (Harv)	43	113	ND	155
Stock Change for Wood Products (from Harvest Removals – 4)	8	23	ND	31
5. Forest Sector–Atmosphere Exchange (from 1 + 2 + 3 + 4; Δ Atmos. C)	16	–201	–32	–217****

Emissions are from 2000 to 2014 for the United States, from 2006 to 2015 for Canada, and the 2000s for Mexico. Exchanges with the atmosphere (e.g., terms 1, 2, 3, 4, 5) are assigned a negative sign for transfers out of the atmosphere (also known as removals or sinks), but the negative sign is dropped in the text when the direction of transfer is specified with terminology. Stock changes in forestlands and in wood products are assigned a positive sign if they are increasing (see Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372, for a review of associated terms).

Notes

a) Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 25-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

b) ECCC (2017). Only includes Canada's managed forests for the 10-year period 2006 to 2015.

c) U.S. EPA (2018). Does not include U.S. territories, Hawai'i, or a large portion of interior Alaska (19.7 million hectares), which are not yet fully integrated into the U.S. national inventory program.

d) INECC/SEMARNAT (2015). Includes effects of forest loss and cyclical uses, which account for some of the emissions that would otherwise appear as releases from harvested wood products.

e) Includes net exchange between the atmosphere and forestland remaining forestland, including disturbance emissions that occur within forests such as those from fire combustion and onsite decay of harvest residues. For the United States, this estimate has been calculated from stock change (see c), plus average harvest removals of about 113 Tg C per year (U.S. EPA 2018).

f) Includes emissions from forest conversion to croplands, wetlands, grasslands, and settlements when reported, and including residual emissions for decades after conversion; overlaps with reporting in other land use, land-use change, and forestry (LULUCF) categories.

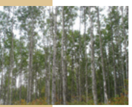
g) Includes emissions (and removals) from all lands converted to forestland through direct human activity; overlaps with reporting in other LULUCF categories.

h) Also referred to as net growth of urban trees; overlaps with reporting in other LULUCF categories.

i) Includes emissions from harvesting removals of biomass of domestic origin and its use in a range of forest products.

j) No data.

k) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.



Box 9.1: Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon

Forests tend to accumulate carbon over time, absorbing carbon dioxide (CO_2) from the atmosphere and storing it as carbon in living biomass, dead organic matter, and mineral soil. The net effect of forests on the atmosphere's store of carbon is reflected in the term "forest net ecosystem production" (NEP_{forest}) or net ecosystem exchange (NEE), which principally represents a forest's metabolic balance between its rate of carbon uptake through photosynthesis and its rate of carbon release as CO_2 through respiration. NEP tends to be positive in forests free of recent disturbance, though climate extremes such as droughts can cause intermittent net carbon releases (NEP < 0).

Disturbance events typically diminish photosynthetic carbon uptake, promptly reducing NEP. Disturbances, including fire and harvesting, also destroy biomass and impose residual respiration releases of carbon from dead biomass as it decays within forests, further decreasing NEP. Fire disturbances (i.e., wildfires and prescribed burns) involve combustion emissions that directly release carbon to the atmosphere, mostly as CO_2 but also as methane, carbon monoxide, volatile organic compounds, and black carbon (see "fire" in Figure 9.2, p. 373).

Harvesting introduces an additional release of forest carbon to the atmosphere through the immediate processing of harvest removals to generate wood products and energy as well as through the combustion and decay of wood products in use. The term F_{HWP} represents the sum of these harvest-related release processes. Some of the harvested biomass (see "harvest" in Figure 9.2, p. 373) is transferred to wood products, a portion of which can reside for decades to centuries either in use (e.g., houses and buildings) or in waste deposits (e.g., landfills). The transfer of forest carbon to long-lived wood products is not itself a direct sink of atmospheric carbon; the sink occurs upstream as part of NEP. Similarly, an increase of carbon stored in wood products should not be interpreted as a sink of atmospheric carbon, but rather the result of a transfer of forest carbon to wood products that exceeds the rate of release of carbon from combustion and decay of legacy wood products. However, if the carbon stocks within a harvested forest recover to their preharvest level faster than releases of the harvested carbon through F_{HWP} plus respiration, a "transient" sink of atmospheric carbon can be created as part of NEP. This sink is transient because it lasts only as long as the excess carbon is stored in wood products, where excess carbon refers to the amount of the originally harvested carbon that has since been recovered by forest regrowth minus the cumulative release of harvested carbon. Correspondingly, shifting harvest removals toward longer-lived wood products can slow F_{HWP}, resulting in an avoided (or delayed) emission of carbon from wood products.

Forest carbon stocks respond not only to the previously mentioned carbon fluxes (e.g., NEPforest, fire, and harvest), but also to gross losses and gains of carbon due to land conversions (AGain and ALoss). Although the reclassification of lands from nonforest to forest (or vice versa) does not itself involve emissions or removals of atmospheric carbon, the processes underlying such reclassifications invariably do. Most important is the residual emission of forest carbon that typically occurs when lands are converted from forest to nonforest. National inventory reports typically include such emissions for 20 years after forest loss, consistent with the estimates in Table 9.3, p. 371, but with methodological differences between countries. Land conversions also complicate agreement between NEE and stock change estimates. For example, NEE for Canada in this chapter was calculated as the average of the annual fluxes on lands classified as forestland remaining forestland (FLFL) in each reporting year, while the stock change was calculated as the carbon stocks on all FLFL lands in 2015 minus the carbon stocks on all FLFL lands in 2006. Because FLFL area decreased over this interval, carbon stocks in FLFL decreased accordingly, with some of the carbon loss appearing as harvest removals, some involving transfer to other land categories, and neither involving immediate emission to the atmosphere (and thus not included in forestland NEE). For the United States, the estimated stock change presented in this chapter only considers lands that persisted as FLFL for the duration of the reporting interval. This estimate was then used to infer an associated NEE in FLFL after accounting for losses from harvest and fire, but at the risk of omitting NEE associated with lands that entered or left the FLFL category during the reporting interval. Methods of assessing carbon transfers, emissions, and removals associated with lands entering or leaving the forestland class are improving and will continue to subtly adjust the larger picture.

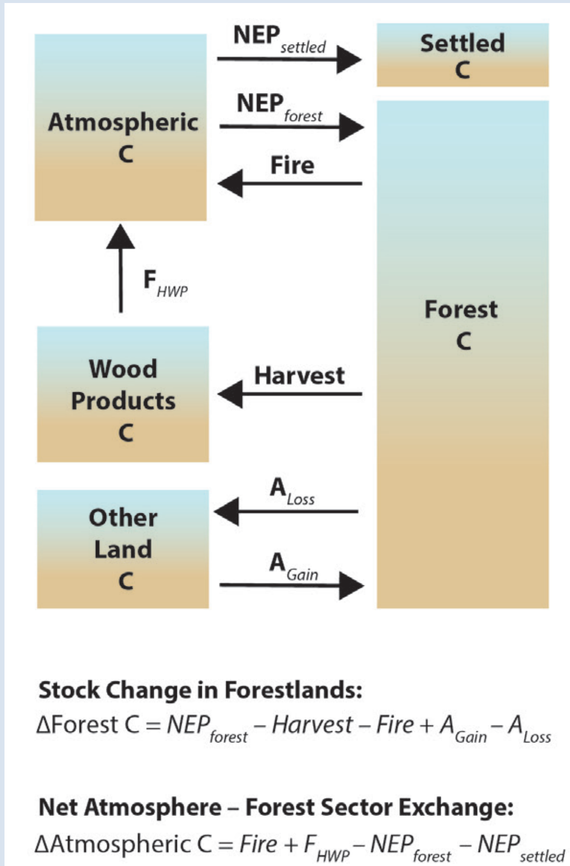
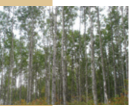


Figure 9.2. Flow Diagram of Active Carbon Exchanges and Stores Between the Atmosphere and the Forest Sector.

The store of carbon in the atmosphere responds to NEP-forest and wooded portions of settled lands ($NEP_{settled}$; see Ch. 4: Understanding Urban Carbon Fluxes, p. 189), plus direct fire emissions from forests and emissions from the decay and combustion of harvest removals (FHWP). The atmosphere does not directly experience the effects of reclassified lands, nor the flow of carbon from forests to the wood products sector, though both have implications for atmospheric carbon as previously noted.

per year (ECCC 2016). In the United States, CH_4 emissions from forest fires equate to a 100-year GWP of 8.3 Tg CO_2e per year, or a 25-year GWP of about 33 Tg CO_2e per year (U.S. EPA 2018).

The Canadian forest sector constituted a near-zero carbon exchange with the atmosphere from 2006 to 2015 as net carbon uptake in intact forests was largely balanced by releases from harvested wood products (ECCC 2017; see Table 9.3, p. 371). Intact Canadian forests took up about 18 Tg C per year over this period, but with large interannual variability ranging from a sink of 248 Tg C to a source of 3.5 Tg C per year. This variability was



driven principally by variability in wildfire emissions, ranging from 3 to 75 Tg C per year from 1990 to 2014 (ECCC 2016). Emissions from harvested wood products were about 43 Tg C per year. These estimates pertain solely to Canada's managed forests, which represent about 66% of the country's total forested area (Stinson et al., 2011). In addition, Canada's urban forests contributed a small sink of 3 Tg C per year while land conversions released 3 Tg C per year, with emissions from forest losses exceeding removals from forest gains (ECCC 2016).

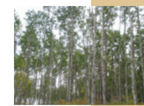
U.S. forests took up atmospheric carbon at a rate of about 267 Tg C per year from 2000 to 2015, contributing to a stock change of 154 Tg C per year (U.S. EPA 2018) after harvest removals of about 113 Tg C per year (U.S. EPA 2018; see Table 9.3, p. 371). This estimate accounts for about 77% of the atmospheric carbon sink in North American forests and includes all managed forestlands in the United States, except for those in interior Alaska (19.7 million ha; U.S. EPA 2018), Hawai'i, and the U.S. territories, all of which are not yet fully integrated into the U.S. national inventory program (U.S. Forest Service 2018). Most of the net sink for atmospheric carbon in U.S. forests is in aboveground carbon pools (U.S. EPA 2018). Urban trees are estimated to uptake another 24 Tg C per year. Net uptake in U.S. forestlands (a sink of 267 Tg C per year) substantially exceeds emissions from harvested wood products estimated at 113 Tg C and the net effect of land conversions, estimated at 0 Tg C per year (U.S. EPA 2018). Interannual variability in U.S. fluxes is reportedly small but may be underestimated by current methods.

Mexico's forests are estimated to uptake about 41 Tg C per year, overwhelming the net effects of land conversion estimated to release 9 Tg C per year (INECC/SEMARNAT 2015). Carbon releases from land clearing still exceed carbon uptake from reforestation, but their net effect is more than offset by carbon uptake in intact and degraded forestlands. This assessment departs from SOCCR1, which reported a sizeable net carbon release from Mexico's forests based on a gain-loss analysis that emphasized land change but omitted consideration of carbon accumulation rates in both intact forests and degraded forests, with a corresponding net uptake of atmospheric carbon. Although a complete methodological description is unavailable, the new data sources and methods used in Mexico's national reporting are believed to provide an improved account of the net carbon uptake in forestlands, which was previously underestimated. Estimates are not available for Mexico's carbon release from harvested wood products and carbon uptake by urban trees.

Net carbon uptake in North American forests as documented in national reports is in broad agreement with results from a wide range of sources (Hayes et al., 2012; King et al., 2015), including 1) atmospheric inversion models (Peylin et al., 2013), 2) syntheses of forest inventory and land-change data (Pan et al., 2011), 3) measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010), and 4) ecosystem process models (Sitch et al., 2015). Regions differ widely in their source and sink patterns and drivers. For example, in the United States, the Northeast has a prevailing legacy of carbon uptake from historical land clearing; in the Southeast, carbon uptake is dominated by regrowth from contemporary harvesting; and carbon releases in the West are increasing because of the recent rise in disturbances and environmental stresses (e.g., droughts, insects, and pathogens; Williams et al., 2016). Fluxes also exhibit large spatial variability at landscape scales (Turner et al., 2016; Williams et al., 2016), with neighboring stands ranging from sources to sinks due to a host of factors including time since disturbance, disturbance type and severity, forest type, local climate, site fertility, topographic position, and other edaphic factors.

9.3.3 Harvested Wood Products

Carbon storage and emissions from harvested wood products (including products in use and in landfills) substantially contribute to overall carbon stocks and fluxes from the forest sector (UNFCCC 2003). Although the contribution of harvested wood products is uncertain, some studies suggest that the



worldwide net increase in harvested wood products amounts to about 8% (189 Tg C per year) of the established global forest sink (Pan et al., 2011; Skog et al., 2004). However, wood product accumulation is the result of harvested wood inputs from forests that exceed releases from the decay and combustion of wood products in use. As such, the wood products pool cannot act as a direct sink for atmospheric carbon, but the store's losses do act as a direct source of atmospheric carbon (see Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372). Nonetheless, in the United States, Skog (2008) indicates that the amount of carbon in harvested wood products grew at a rate of 25 to 36 Tg C per year from 1990 to 2005. Canada reports an increase in wood products of about 12 to 17 Tg C per year over the same time period, slowing to about 8 Tg C per year from 2006 to 2015 (ECCC 2017). These net increases result from inputs exceeding losses. For example, in the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg C per year) was offset by releases (84 Tg C per year), yielding a corresponding increase in wood products of 26 Tg C (U.S. EPA 2018, Annex 3b, Table A-240). Importantly, the net increase in the harvested wood products pool is contingent upon a sustained or growing rate of harvest removals of forest carbon, or a shift toward products that have a longer residence time. If harvest rates decline (as they did during the economic recession of 2008), net additions to harvested wood products may be lower than emissions from wood harvested in prior years, as was the case in the eastern United States (U.S. EPA 2018).

In 2009, the annual increase in harvested wood products slowed to 15 Tg C and 0 Tg C per year for the United States and Canada, respectively, driven by slowing economic markets, particularly housing. As economies recover, additions to the harvested wood products pool are now returning to prerecession levels, indicating the pool's strong sensitivity to markets. Looking ahead, carbon storage in harvested wood products is expected to increase by about 7 to 8 Tg C per year over the next 25 years (U.S. Department of State 2016).

9.4 Attribution and Trends

9.4.1 Overview

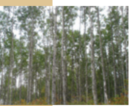
Many of the factors identified in SOCCR1 (CCSP 2007) continue to be important drivers of change in carbon stocks of forest ecosystems and wood products (CCSP 2007). North American forests are highly diverse, and many are changing rapidly. Management (e.g., timber harvesting and cyclical forest uses) is a major driver of carbon dynamics. Land conversions may cause net carbon emissions in North America, even in the United States where gross gains in forestland exceed gross losses. The changing climate and atmospheric chemistry (e.g., nitrogen deposition, tropospheric ozone, and rising atmospheric CO_2 concentrations) are modifying forest growth rates, growth potential, and mortality. Natural disturbances (e.g., wind, fire, and insects and disease) are generally accelerating mortality and modifying forest composition. All these drivers, and their ongoing trends, have important implications for forest carbon policy and management.

9.4.2 Land Use and Land-Use Change

Land use and land-use change can have major implications for land carbon stocks and fluxes and thus are key requirements for UNFCCC reporting. Land-use change, including conversion of nonforestland to forestland, in European nations (Nabuurs et al., 2013) and the United States (Woodall et al., 2015), has taken up a sizeable amount of atmospheric CO_2 since 1990, but this effect is expected to slow in the near future (Coulston et al., 2015; Nabuurs et al., 2013).

The current rate of land-use change in Canada is small, with about 0.02% of Canada's forest area lost each year through deforestation (Dyk et al., 2015; ECCC 2016) or about 30,000 ha of forest lost per year from 2006 to 2015 (ECCC 2017). The gain in forest area through afforestation, vegetation thickening, and expansion of tree lines northward and to higher elevations is not known, so the net balance of forest area change cannot be determined.

In Mexico, land converted to forest contributes a sink of atmospheric carbon of 3.4 Tg C per year.



This sink is more than offset by carbon losses from forest conversion, leading to net carbon emissions of about 8.8 Tg C per year from the balance of forest gains and losses in Mexico (see Table 9.3, p. 371; INECC/SEMARNAT 2015).

Deforestation in the United States occurs at a rate of about 0.12% per year, or 355,000 ha per year (Masek et al., 2011), but is more than offset by forest gain from afforestation. The net effect is a gain in U.S. forest land area of about 0.15% per year, or 430,000 ha per year (Smith et al., 2009; U.S. EPA 2018) between 2006 and 2015, largely converted from grasslands and croplands (U.S. EPA 2018). This nationwide assessment of net changes in forest area masks important region-specific patterns, with the North and Rocky Mountains seeing net gains in forest land area over the past couple decades and the Pacific Coast and South seeing net losses (Smith et al., 2009). The estimated net carbon flux in the United States associated with forestland conversion is approximately zero, with gains in forestland constituting a sink of atmospheric carbon of 23 Tg C per year and losses resulting in emissions of 23 Tg C per year (see Table 9.3, p. 371; U.S. EPA 2018).

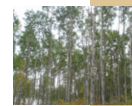
9.4.3 Forest Management

Nearly two-thirds of Canada's forests and nearly all forests in the conterminous United States are considered managed lands. Human activities directly influence these lands, and management is mainly for wood products, water, and recreation services, with carbon uptake a secondary outcome. In many of these regions, forest carbon stocks are recovering from historical clearing and thinning dating back to as early as the 1600s. This recovery stimulates forest carbon uptake from both afforestation and carbon accumulation in still-maturing stands. Forest management also has 1) altered forest species composition (e.g., with the establishment of plantations); 2) generally accelerated carbon accumulation rates (Erb et al., 2013); and 3) modified forest soil fertility, both through nutrient gains from fertilizer application and nutrient losses from erosion caused by some harvesting practices. The net effect of such activities on forest carbon stocks and fluxes is unclear. Fire suppression activities have tended to increase forest carbon stocks, and, along with grazing practices, may contribute to woody encroachment. Fuel reduction treatments (e.g., prescribed fire and thinning) often are intended to lower the risk of severe wildfire by reducing crown density, thinning the understory, and reducing fuel loads, all of which may contribute to short-term carbon losses. However, these treatments often lead to carbon storage in wood products, protection of residual trees, and increased growth through reduction of resource competition. Collectively, therefore, fuel reduction treatments may contribute to greater long-term carbon storage than untreated stands (Hurteau et al., 2008; Loudermilk et al., 2016).

9.4.4 Climate and Atmospheric Chemistry

Climate change and extreme weather events, as well as changes in atmospheric chemistry (e.g., nitrogen deposition, tropospheric ozone, and rising atmospheric CO_2 concentrations), affect carbon cycling in forests (Ollinger et al., 2002; Sun et al., 2015; Templer et al., 2012). In general, rising temperatures (Melillo et al., 2011) and atmospheric CO_2 concentrations (Norby et al., 2005) stimulate forest productivity, but the magnitude of these effects depends on soil fertility, particularly nitrogen and phosphorous availability, and the composition of the soil microbial community (Drake et al., 2011; Finzi and Schlesinger 2002; Terrer et al., 2016). Atmospheric nitrogen deposition can increase soil fertility (Thomas et al., 2010), counteract soil resource limitations (e.g., Johnson et al., 1998; Oren et al., 2001), and directly enhance tree growth (Thomas et al., 2010). Climate-induced changes in precipitation may alter soil carbon dynamics and vegetation carbon uptake during periods of inundation, lead to flooding-related tree mortality, and cause soil erosion with losses of particulate and dissolved organic carbon from forests (Frank et al., 2015).

Although some climatic and atmospheric changes can stimulate productivity, they also can negatively affect forest carbon sinks. High temperatures can induce heat-related stress in plants (Peng et al., 2011), worsen drought conditions (Diffenbaugh



et al., 2015), and lead to higher mortality and lower productivity in ecosystems (Anderegg et al., 2015a; Birdsey and Pan 2011). Climate warming also increases night-time ecosystem respiration and reduces net ecosystem production (NEP; Anderegg et al., 2015b). Similarly, the positive effect of rising atmospheric CO_2 and nitrogen availability on net primary production (NPP) can be moderated by elevated tropospheric ozone, which damages plants, reducing their health and productivity (Karnosky et al., 2003; Loya et al., 2003; Pan et al., 2009). Rates of sulfur deposition have declined in recent years, but acid deposition from excess nitrogen remains elevated and contributes to lower soil pH; depletion of labile cations, such as calcium, needed for plant growth (Likens et al., 1996, 2001); and mobilization of aluminum, which is toxic to plants (Aber et al., 1998). The effects of acid deposition on forest carbon storage are mediated through stand age, soil type (e.g., cation-poor sandstones versus calcium-rich limestone), and ultimately the fate of deposited nitrogen. Excess nitrogen deposition can result in nitrogen saturation of biotic and abiotic sinks, altering ecosystem carbon allocation, and lead to a cascade of negative effects on water and air quality that decrease forest productivity. The United States is a global hotspot of nitrogen emissions and deposition, with a steady rate of wet deposition of dissolved inorganic nitrogen from 1985 to 2012. However, the contribution from ammonium has increased relative to nitrate, and deposition is higher in the Midwest and Northeast than in the South and West (Du et al., 2014).

Stimulatory effects of rising CO_2 on aboveground forest productivity have not been matched by a concomitant increase in soil carbon, the largest carbon pool in forests and one that does not turn over very quickly (Lichter et al., 2008; van Groenigen et al., 2014). Thus, larger litter inputs to soils without an increase in soil carbon stocks implies an accelerated rate of carbon cycling in global forest ecosystems (Pan et al., 2013). Moreover, GHGs are returned to the atmosphere through emissions of CO_2 from harvested products; emissions of CO_2, CH_4, and nitrous oxide (N_2O) from biomass burning; and evasion of CO_2 from streams and rivers (Kim and Tanaka 2003; Turner et al., 2013). These emissions are expected to offset a portion of the gains in productivity from afforestation following disturbance and climatic and atmospheric changes (Turner et al., 2013). Furthermore, severe warming of forest soils has been shown to accelerate soil organic matter decay and result in net loss of soil carbon emitted as CO_2 (Melillo et al., 2017). Given the wide range of forest responses, better understanding of the effects of climatic and atmospheric changes continues to be a high research priority in the United States.

9.4.5 Natural Disturbances

Natural disturbances are widespread across North America (see Figure 9.3, p. 378) and play an important role in the forest carbon cycle (Hicke et al., 2012; Odum 1969; Williams et al., 2016), affecting NPP and heterotrophic respiration, transferring carbon from live to dead pools, and involving direct emissions (e.g., from fires [French et al., 2011; Ghimire et al., 2012]). These disturbances include wildfires, insects and pathogens, droughts, floods, and severe wind events (Frank et al., 2015; Tian et al., 2015). Severe disturbances typically cause an immediate reduction in stand-level productivity, transfer carbon from live to dead stores, and increase decomposition. These effects generally are followed by a gradual increase in productivity and decrease in decomposition as the stand recovers. Initial net carbon release immediately after severe disturbances gives way to net carbon uptake as a forest regrows, but the full effect on atmospheric CO_2 depends also on the timing of disturbance-induced CO_2 releases. Carbon impacts of disturbance vary with several key features including disturbance type and severity, temporal sequence of events, and biotic and climatic conditions of regeneration (Hicke et al., 2012; Williams et al., 2016).

The extent, severity, and frequency of natural disturbances have increased in recent decades (Allen et al., 2010; Hicke et al., 2013; see Figure 9.4, p. 379), likely influenced by recent climate change and human activities. Western regions of Canada and the United States have experienced substantial die-offs recently from wildfire, insect outbreak,

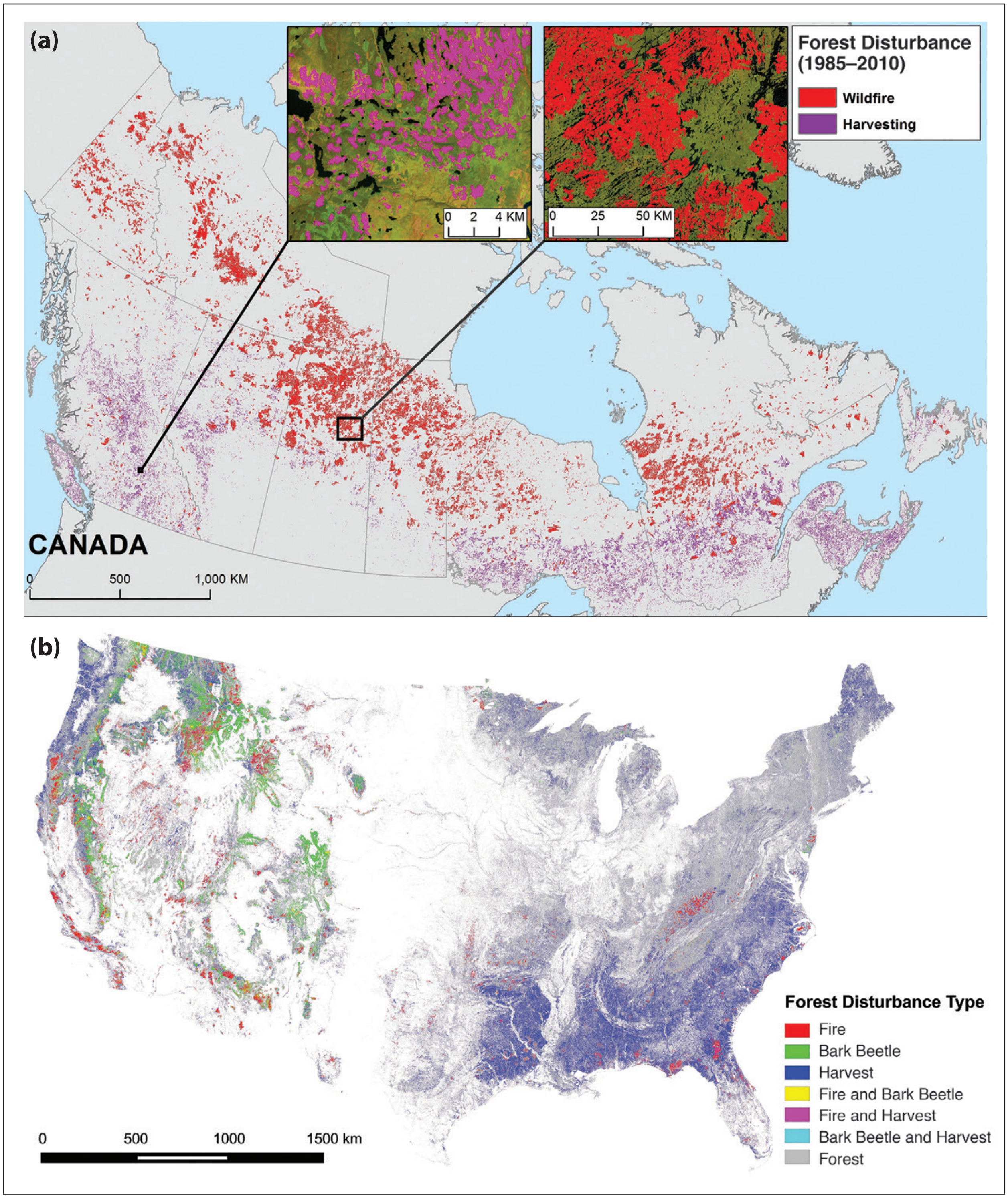


Figure 9.3. Satellite-Derived Distribution of Major Forest Disturbances by Type for Canada (a) and the United States (b). Canadian disturbance data, spanning 1985 to 2010, are based on Hermosilla et al. (2016) and White et al. (2017). U.S. disturbance data (based on Williams et al., 2016) include harvests from 1986 to 2010, fires from 1984 to 2014, and bark beetles from 1997 to 2014. [Figure sources: **(a)** Mike Wulder and Joanne White, Canadian Forest Service, Natural Resources Canada. **(b)** Reprinted from Williams et al., 2016, copyright Elsevier, used with permission.]

and drought disturbances. These events have led to widespread tree mortality, with fire and insects alone affecting up to 9% of the live tree carbon stocks in western U.S. forests (Ghimire et al., 2012, 2015; Hicke et al., 2013) and with insects also having a substantial and prolonged effect in British Columbia (Kurz et al., 2008a, 2008b). Disturbance impacts on region-wide carbon dynamics can be large and result in sizeable interannual variability in the forest carbon balance (see Figure 9.5, p. 380), and landscapes often contain offsetting effects of large carbon releases in small areas that recently experienced severe disturbance and modest carbon uptake in larger areas at various stages of recovery from prior disturbance. In eastern North America, native and invasive forest insects play important roles locally (Clark et al., 2010) and regionally (Kurz and Apps 1999). Insect damage in the United States is estimated to result in the loss of about 20 Tg of live carbon stocks per year, though release to the atmosphere through decomposition can be delayed for decades. Similar, if not larger, losses have been reported for Canada (Kurz et al., 2008a, 2008b). U.S. wildfires lead to emissions of about 40 Tg C per year, with large year to year variability. Windstorms cause an average annual loss of about 35 Tg of live carbon stocks in the United States alone (Williams et al., 2016), largely from hurricanes in the Southeast that have major individual impacts (Chambers et al., 2007; Fisk et al., 2013). Windstorm losses of live biomass are released to the atmosphere only gradually and typically are offset by forest regrowth, leading to a steady long-term effect on atmospheric carbon (Fisk et al., 2013; Zeng et al., 2009). Droughts in the United States and Canada have resulted in punctuated and widespread reductions in forest productivity (Schwalm et al., 2010) as well as tree mortality (Anderegg et al., 2013a, 2013b; Hogg et al., 2008; Michaelian et al., 2011; Peng et al., 2011; Potter 2016; van Mantgem et al., 2009) that together can cause sizeable declines in NEP and the strength of the forest carbon sink (Brzostek et al., 2014; Ma et al., 2012; Schwalm et al., 2012).

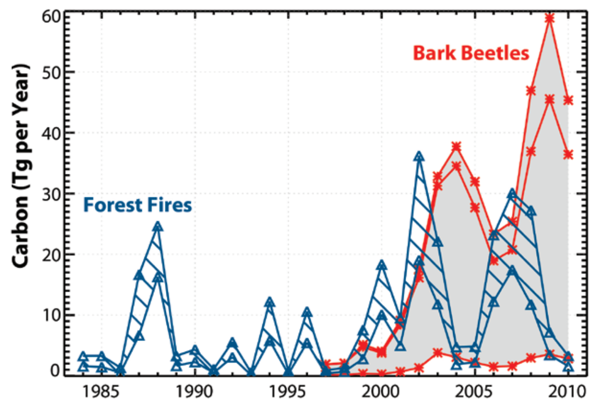


Figure 9.4. Teragrams (Tg) of Carbon in Western U.S. Trees Killed by Disturbances. The impacts of major bark beetle disturbances (1997 to 2010; red lines represent upper, middle, and lower estimates; gray shading indicates range between upper and lower estimates) and forest fires (1984 to 2010; blue lines represent moderate and moderate plus high-severity burned areas; hatching indicates range between moderate and moderate plus high-severity burned areas) are shown. [Figure source: Redrawn from Hicke et al., 2013, used with permission under a Creative Commons license (CC_By_3.0).]

9.4.6 Projections

Accounting for land-use change, management, disturbance, and forest aging, some models project that U.S. forests will continue taking up carbon but at declining rates, largely because of land-use dynamics and aging forests (USDA-OCE 2016; Wear and Coulston 2015). After 20 years of net gains, forest area is projected to level and then decline gradually after 2030 due to ongoing population growth and declining afforestation on agricultural lands (U.S. Forest Service 2012; Wear and Coulston 2015), though projections differ depending on assumptions about how macroeconomic and market trends will drive land use. In the western United States, aging forests coupled with disturbance dynamics are projected to diminish carbon uptake to negligible levels by midcentury. In the East, younger productive forests are expected to have high carbon uptake rates, though harvest-related emissions substantially reduce the net effect on atmospheric carbon.

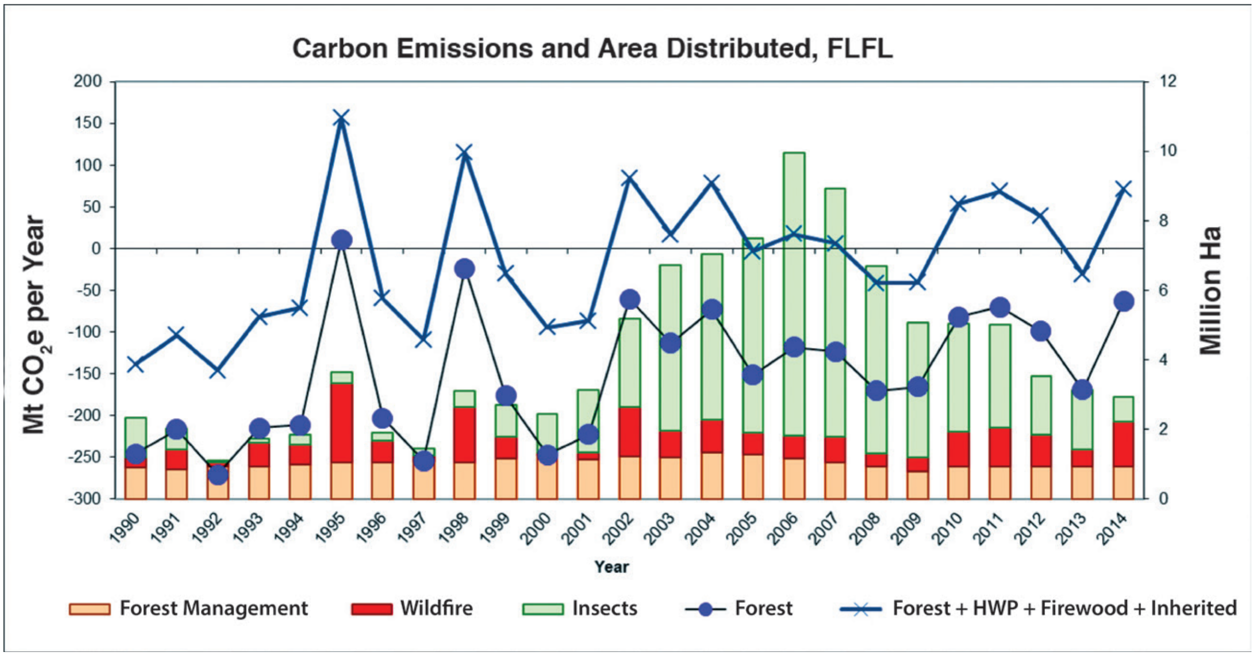


Figure 9.5. Effects of Natural Disturbances on Carbon Dynamics in Canada's Managed Forests. Disturbances such as wildfire and insects contribute to very large interannual variability in greenhouse gas (GHG) emissions and removals on the hectares (ha) of Canadian forestland remaining forestland (FLFL). Emissions include carbon dioxide (CO_2) and non-CO_2 GHGs converted to CO_2 equivalents (CO_2e). Forest fluxes are exchanges with the atmosphere, not counting the lateral transfer of harvested wood to the products sector. The upper line includes the forest carbon sink plus annual emissions from the harvested wood products sector, including firewood burning and annual emissions from wood harvested since 1941, regardless of where the wood was oxidized. [Figure sources: Adapted from ECCC 2016 and Stinson et al., 2011, used with permission.]

Climate change defines complex and uncertain adjustments to net carbon accumulation in forests. Several studies suggest that atmospheric enrichment from CO_2 and nitrogen could increase biomass growth by 0% to 2% annually (Fang et al., 2014; Schimel 2007; Shevliakova et al., 2013). Meanwhile, climate change generally is expected to increase the frequency and severity of natural disturbances in North America in the coming decades, potentially reducing forest carbon stocks considerably (Peterson et al., 2014; U.S. Forest Service 2012). Other climate change impacts—including shifts in growing season length, water availability, and temperature—will interact with atmospheric changes to determine forest growth responses (Gedalof and Berg 2010; McCarthy et al., 2006). Projection experiments that include a trend of increased productivity (+0.4%), coupled with forest age, disturbance, and management dynamics, indicate some potential for additional carbon uptake over baseline levels described previously (+5.1% from 2015 to 2050; Wear and Coulston 2015). However, increases are small relative to the projected changes for all other driving variables. Forest sink strength is likely to diminish gradually over the next 20 years as forest area gains tail off and forests continue to age. Uncertainty regarding the future carbon balance of North American forests increases with time. There is some potential for enhanced productivity resulting in a larger carbon sink, but disturbance rates and other elements of global change could increase carbon emissions from forests (Kurz et al., 2013; Lemprière et al., 2008). Uncertainties about the impacts of global change remain high. Increased sinks are unlikely to be of sufficient magnitude to offset higher emissions from increased disturbances and enhanced release of carbon from decomposition (Kurz et al., 2013). However, the forest sink in the eastern temperate zone of North America is expected to be relatively stable despite these pressures (Wear and Coulston 2015).

9.5 Global Perspective

The North American forest carbon sink of 217 Tg C reported in this chapter represents about 20% of the global net forest carbon sink (Pan et al., 2011) on forest area that is 18% of the global total (FAO 2016b). Most of the North American carbon sink is in temperate U.S. forests that are managed relatively intensively for wood products and other services, indicating that managed forests typically are maintained with a lower stand density and lower carbon stocks than mature forests but have potentially higher growth rates. Current carbon stocks of North American forests average 155.4 Mg C per hectare, which is about 69% of the average for global forests (Pan et al., 2011), indicating higher-than-average carbon uptake and substantial capacity to increase average carbon stocks. According to the most comprehensive global estimates (FAO 2016a; Nabuurs et al., 2007), the mitigation potential of North American forests represents about 15% of the global forest mitigation potential for forestry activities according to “bottom-up” studies, sufficient to offset 2% of global CO_2 emissions (Le Quéré et al., 2015). The main mitigation activities for North American forests include reducing deforestation, increasing afforestation, and improving forest management—activities that are most viable in tropical and temperate biomes (FAO 2016a; Nabuurs et al., 2007).

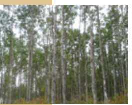
9.6 Societal Drivers and Impacts

Atmospheric CO_2 uptake in U.S. forests has partially offset carbon emissions in other sectors of the U.S. economy. The 2014 net uptake estimate from forestland remaining forestland was 742 Tg CO_2e per year, which offset about 11% of gross U.S. GHG emissions. Assuming no policy intervention, the U.S. Department of Agriculture (USDA) reference scenario developed for the 2016 U.S. Biennial Report (USDA-OCE 2016) projects that annual carbon uptake will decrease to 320 Tg CO_2e per year in 2050 as a result of forest aging, forest disturbance, and land-use change.

Government policies to boost forest carbon uptake have the potential to slow its projected decline. Available options include altering (e.g., slowing, intensifying, or redirecting) development and increasing afforestation of private land in the eastern United States (12 million ha) and reforestation of public land in the western United States (5 million ha) to achieve no net loss of forest area beginning in 2025. Relative to the reference scenario, this option is projected to increase cumulative carbon uptake by 26% from 2015 to 2060 (USDA-OCE 2016).

One way to estimate the societal impact of policy options to increase forest carbon uptake is to estimate the benefit in terms of avoided damages resulting from a net carbon emissions reduction. This benefit is estimated using social cost of carbon (SCC) estimates, which are dollar estimates of the long-term damage done by a ton of CO_2 emissions in a given year. One report indicates that the SCC would increase from $42 in 2015 per 0.9 Mg CO_2e emitted to $80 in 2050, which can be translated to equivalent savings for uptake of CO_2e (using an average annual discount rate of 3%, with values in 2016 U.S. dollars; U.S. Interagency Working Group on Social Cost of Carbon 2013). As an example of the potential benefit of exploring policy options to boost forest carbon uptake, the current value of increased forest carbon uptake under a policy that reduces land development and increases afforestation and reforestation relative to the reference scenario is $132 billion (Bluffstone et al., 2017).

A policy option that involves afforestation of private forestland to increase forest carbon uptake could be achieved with incentives to private landowners. The USDA has five voluntary incentive programs, which account for more than 95% of USDA conservation spending (USDA-ERS 2014). When estimating benefits of incentive programs to increase forest carbon uptake, problems of “additionality” and “leakage” may lead to overestimating carbon uptake



gains (Lubowski et al., 2006). Estimates of forest carbon uptake by voluntary incentives may not be fully additional because some of this carbon would have been taken up on private forestland without the program. Furthermore, leakage could occur if landowners clear forestland for farming to compensate for land enrolled in the incentive program. Both additionality and leakage need to be accounted for when estimating the benefits of incentive programs to increase carbon uptake on private forestlands.

9.7 Carbon Management

Forest management activities have the potential to sustain and enhance the role of the North American forest sector in mitigating rising GHG concentrations over the next century. Key opportunities include 1) avoided deforestation emissions, 2) carbon uptake with afforestation and management to enhance stock growth, and 3) harvest removals directed toward clean energy options, including using logging residues and waste wood as a substitute for fossil fuels and long-lived wood products to replace building materials such as cement and steel that are more carbon emissions intensive (Birdsey et al., 2006; Lemprière et al., 2013).

Slowing deforestation and targeting clearings toward lands with lower carbon density could reduce carbon emissions substantially (Lemprière et al., 2013). Reducing harvest intensity, lengthening harvest rotations, and increasing stand densities are additional leading options because they generally increase carbon stocks in the absence of severe disturbance (Creutzburg et al., 2017; D'Amato et al., 2011; Harmon and Marks 2002; Perez-Garcia et al., 2007; Taylor et al., 2008). McKinley et al. (2011) reported that a combination of longer harvest intervals, management to increase vegetation growth rates, and establishment of preserves may increase carbon uptake by 30 to 105 Tg C per year in the United States alone. Important to note, however, is that slowing deforestation and harvesting in one region may simply displace such activities (i.e., leakage) if unmatched by a change in the demand for associated land uses and forest products. Moreover, increased carbon stocks in areas prone to severe disturbance may not act as a lasting sink for atmospheric carbon.

Forestry activities also may be adapted to promote soil carbon maintenance and transfer by minimizing disturbances to soil and stand structure and increasing forest productivity and the inputs to the soil (Canadell and Raupach 2008; Jandl et al., 2007). Other forestry efforts can minimize impacts to belowground carbon stocks associated with some management and harvesting activities (Nave et al., 2010; Noormets et al., 2015). Fuel reduction treatments that aim to lower severe fire risk may constitute a limited future sink for atmospheric carbon if expected future fire emissions could be reduced more than the carbon emissions from prescribed burning and mechanical removal (Hurteau and North 2009). Treatments that utilize wood removals for bioenergy may have additional mitigation benefits depending on the type of woody material used (harvest residues versus whole trees) and the fate of that material in the absence of fuel-reduction treatments (Dale et al., 2017). However, treatment areas tend to be much larger than the area they ultimately protect, so the net benefits over large landscapes may not be realized (Boer et al., 2015; Campbell et al., 2012; Hudiburg et al., 2013; Loehman et al., 2014).

Regarding afforestation, the potential for increasing carbon uptake in the United States alone is high, given that 1) the country's current forestland amounts to about 72% of that in 1630 (Smith et al., 2009) and 2) 60% of the CO_2 emitted from forest harvesting in the United States a century ago has yet to be resequestered (McKinley et al., 2011). U.S. afforestation alone could yield 1 to 225 Tg of additional forest carbon uptake per year in coming decades (McKinley et al., 2011). However, there are major practical limits to widespread implementation since the higher levels of afforestation would require taking land from other uses such as food production (Ray et al., 2009). In Canada, afforestation could add up to 59 Tg C per year (Lemprière et al., 2013). In Mexico, minimal data are available on the carbon

uptake potential of afforestation, or even forest management in general.

Another potential opportunity for reducing carbon emissions is shifting harvested wood from short-lived products toward uses with slower or no carbon release to the atmosphere (Bellassen and Luyssaert 2014; Lemprière et al., 2013; Oliver et al., 2014). An additional possibility is the use of forest biomass as a substitute for fossil fuels for energy production (Miner et al., 2014). Worth noting, however, is that long time frames, accurate counterfactuals, and full life cycle assessments often are needed to estimate the mitigation benefits of these and other carbon management activities, including bioenergy (Hudiburg et al., 2013; McKechnie et al., 2011; Perez-Garcia et al., 2007).

Estimates of the potential for forest management to mitigate rising GHGs vary widely because of uncertainties, mainly in natural disturbances, leakage effects, and carbon markets (Anderegg et al., 2015b; ECCC 2016; Gough et al., 2016; Harmon et al., 2011). Climate change effects are also uncertain and differ by forest type and location, making climate-adaptive forest management increasingly important (Duveneck and Scheller 2015). Assessment of carbon management opportunities may need to include consideration of vulnerability to disturbances. For example, locating carbon uptake activities in low-disturbance environments may be appropriate, along with perhaps focusing carbon emission actions (e.g., harvesting and land clearings) in higher-disturbance environments.

In the future, forest carbon management likely will be a co-benefit of many other forest uses and values. Owners and managers may decide to maintain lower carbon stocks as a side effect of pursuing other values, such as promoting habitat for select wildlife and reducing risk of severe wildfires.

9.8 Synthesis, Knowledge Gaps, and Outlook

9.8.1 Synthesis

Net carbon uptake by North American forests is well documented. Its strength varies regionally, with about 80% of the North American forest sink for atmospheric carbon occurring within the United States. Attributing North America's forest carbon sink to drivers remains difficult. Forest regrowth following historical clearing plays a role, but studies also suggest sizeable contributions from growth enhancements such as CO_2 fertilization, nitrogen deposition, or climate trends supporting accelerated growth. Resolving each factor's contribution is a major challenge and critical for developing reliable predictions. Several factors driving this sink are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake in the near term, possibly giving way to increased net carbon uptake in the more distant future if forests fully recover from today's disturbance trends.

Intensive forestry in select regions causes large annual reductions in forest carbon stocks that are eventually compensated for by forest regrowth, often over decades, if biomass recovers to preharvest conditions. However, carbon releases from the associated decay of harvested wood products offset a substantial portion (about half) of the net carbon sink in North American forests. Recent trends in natural disturbance rates have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions also reduces sink strength across the continent, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation.

9.8.2 Gaps

Forests across North America are quite diverse. Although much is known about this diversity, datasets are still needed to characterize forest conditions at the scale of disturbance and management units (e.g., stand scale, ~30 m × 30 m). Such data would provide managers with the information necessary to design and implement effective carbon policy and management aiming to increase carbon uptake or reduce emissions. Maps of site productivity, stand age, and biomass at a stand scale (e.g., 30 m) would be particularly valuable, offering practical improvements to current assessment capabilities.

Remeasurement data on tree- and stand-scale carbon stocks—including standing dead and downed wood and soil carbon pools and their turnover rates—are needed to record contemporary rates of carbon accumulation, improve understanding of net carbon uptake drivers, and aid assessment frameworks and models required for prediction. Also needed are analyses of expected shifts in forest composition in response to trends in climate; atmospheric composition; disturbances; the establishment and spread of invasive and/or exotic insects, pathogens, and plants; and management to improve projections of future carbon dynamics beyond an assumption of steady forest compositions and static ecotones. Conclusive evaluation of the rate and magnitude of woody encroachment is still lacking. Delivery of forest carbon to wetlands and waterways via erosion and drainage also is poorly quantified, despite its importance for continental-scale carbon budgeting and management.

Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and other studies reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions involving legacies of flammability and host species presence and absence, as well as active management responses such as fuel reduction treatments or preemptive and salvage logging. Also needed is knowledge of how belowground carbon stocks change as lands transition across uses over time (Domke et al., 2016). These gaps challenge assessments of legacy emissions and post-disturbance recovery and hamper attempts to quantify the potential of management activities to promote long-lived forest carbon sinks and reduce carbon emissions.

The use of remote sensing (e.g., Landsat) has led to major advances over the past decade in monitoring aspects of disturbance and land-use change (Bachelet et al., 2015; Hansen et al., 2013), but major research gaps remain. Disturbance histories at the stand scale and attribution to disturbance type and severity remain poorly characterized, as are rates of forest conversion. Improved estimates of the location, severity, and timing of natural disturbances are needed, particularly in Mexico. Degradation of forest stocks (e.g., from selective logging, low-severity disturbances, and stress) also remain poorly characterized at the scales needed for assessing carbon dynamics and managing forest carbon. Landscape-scale records of management practices such as replanting, selective harvesting, cyclical use, and agroforestry also are needed. Integration of a range of remote-sensing technologies, including light detection and ranging (LIDAR), with field plot data and carbon cycle modeling, promises to substantially improve the ability to measure and monitor forest carbon dynamics at large scales. Addressing these and other gaps ultimately will lead to spatially explicit estimates of carbon stocks and fluxes that comprehensively assess impacts of disturbance, management, and environmental changes on carbon fluxes.

Coupled experiments and models as well as multifactor manipulations are needed to better understand carbon cycling in forest ecosystems and the drivers contributing to carbon dynamics. Full life cycle analyses are required to improve understanding of today's carbon sinks in a longer temporal context, account for the full effects of management and global change drivers, and evaluate the costs and benefits of substituting wood products for other building materials or energy sources. Also needed is better information on the origin and fate of harvested wood products, which should enable more accurate and comprehensive estimation of harvesting impacts.

Collectively, the large uncertainties and substantial variation in model predictions and GHG inventory estimates can be attributed to the gaps identified in this section. Future assessments should attempt to better integrate data sources and products and move beyond a focus on forest carbon exchange with the atmosphere toward full climate impact assessment such as in Anderson-Teixeira et al. (2012). Considerations are needed of 1) albedo changes from forest change, 2) CH_4 and N_2O fluxes, and 3) dynamics of other radiatively active atmospheric constituents such as aerosols and black carbon.

Also needed are management and planning tools (e.g., see Figure 9.6, this page) designed to help develop and evaluate alternative landscape-scale strategies for managing forests to address a range of ecosystem services including carbon. Platforms, such as the Forest Vegetation Simulator (FVS; www.fs.fed.us/fmsc/fvs/) and i-Tree (www.itreetools.org), enable assessment of impacts from disturbance trends and management scenarios in the context of uncertain global environmental changes to inform policymakers, land managers, industry, and the public. Such platforms can be designed to consider a wide range of ecosystem values beyond carbon to assess full climate forcing (i.e., albedo impacts), as well as biodiversity, habitat, water quality and quantity, timber production, disturbance avoidance, and other goods and services. Moreover, these platforms can be designed to flexibly handle uncertainty in forest responses to changes in climate and interactive trends in management and natural disturbance regimes.

9.8.3 Outlook

Climate change is influencing forest carbon in diverse ways, supporting enhanced carbon uptake in some regions by lengthening growing seasons and elevating CO_2 supply to photosynthesis. However, climate change also is leading to plant stress that reduces growth, increases the likelihood of mortality, and supports more extensive and severe disturbance-induced releases of carbon. All these drivers are altering the ecology and natural resources of North America's forests. How these processes and

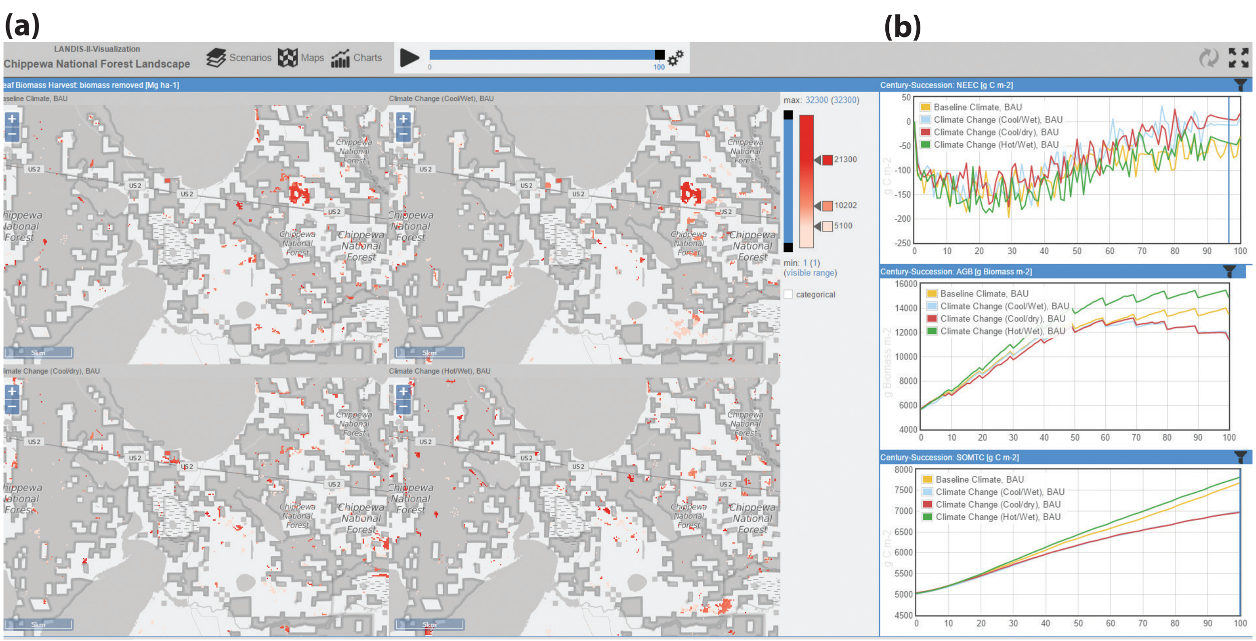
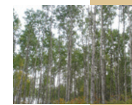


Figure 9.6. LandViz: A Forest Management and Planning Tool. LandViz maps and charts are generated for harvested timber **(a)** and carbon uptake rates, aboveground biomass, and soil carbon **(b)** using a forest simulation model (LANDIS-II) under historic climate and three climate change scenarios. LandViz is a visualization tool designed for forest managers to facilitate the integration of climate change results into the forest planning process. [Figure source: LandViz, Gustafson et al., 2016.]

their net effect will unfold over coming decades remains unclear.

Harvesting is the dominant forest management activity affecting carbon dynamics in North American forests; it has a net effect of reducing land carbon stocks and emitting carbon to the atmosphere. Slowing harvesting rates or modifying cutting practices could affect future forest carbon stocks significantly.

Several management activities could increase forest uptake of atmospheric carbon and decrease emissions in the forest sector (Birdsey et al., 2006; McKinley et al., 2011; Post et al., 2012). These activities include delaying or avoiding emissions from wood products by producing renewable building materials and developing energy sources with lower life cycle emissions than their GHG-intensive alternatives. Management through afforestation also may promote rapid regrowth of carbon stocks within forests (Erb et al., 2013) and even expand forestlands (Birdsey et al., 2006). However, practical limits are likely to severely constrain implementation, along with competition with other management and use objectives (Ray et al., 2009). Although climate mitigation activities, and associated carbon markets, remain highly uncertain, they clearly have the potential to substantially influence the priority placed on forest management to promote forest sector carbon storage.



SUPPORTING EVIDENCE

KEY FINDING 1

Net uptake of 217 teragrams of carbon (Tg C) per year by the forest sector in North America is well documented and has persisted at about this level over the last decade. The strength of net carbon uptake varies regionally, with about 80% of the North American forest carbon sink occurring within the United States (*high confidence, very likely*).

Description of evidence base

Net carbon uptake in North American forests, as documented in national inventory reports from Canada (ECCC 2016), Mexico (INECC/SEMARNAT 2015), and the United States (U.S. EPA 2018), is in broad agreement with results from a wide range of sources (Hayes et al., 2012; King et al., 2015). These sources include atmospheric inversion models (Peylin et al., 2013), syntheses of forest inventory and land-change data (Pan et al., 2011), measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010), and ecosystem process models (Sitch et al., 2015).

Major uncertainties

Regions differ widely in their source and sink patterns and drivers. For example, in the United States, the Northeast has a prevailing legacy of carbon uptake from historical land clearing; in the Southeast, carbon uptake is dominated by regrowth from contemporary harvesting; and the West has increasing carbon releases from the recent rise in environmental stresses (e.g., droughts, insects, and pathogens) and disturbances (Williams et al., 2016). Fluxes also exhibit large spatial variability at landscape scales (Turner et al., 2016; Williams et al., 2014), with neighboring stands ranging from sources to sinks because of a host of factors including time since disturbance, disturbance type and severity, forest type, local climate, site fertility, topographic position, and other edaphic factors.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

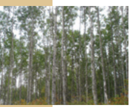
While some uncertainty remains about the spatial patterns and drivers of carbon sources and sinks across the continent, multiple lines of evidence converge to provide high confidence regarding the magnitude of net carbon uptake across North America's forests in recent decades.

Summary sentence or paragraph that integrates the above information

It is highly likely that North American forests represent a net sink of carbon, given the convergence in evidence across multiple inventory, scaling, and modeling approaches in Canada, Mexico, and the United States.

KEY FINDING 2

Forest regrowth following historical clearing plays a substantial role in determining the size of the forest carbon sink, but studies also suggest sizeable contributions from growth enhancements such as carbon dioxide (CO_2) fertilization, nitrogen deposition, or climate trends supporting accelerated growth (*medium confidence*). Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.



Description of evidence base

Although the use of remote sensing (e.g., Landsat) has led to major advances over the past decade in monitoring aspects of disturbance and land-use change (Bachelet et al., 2015; Hansen et al., 2013), critical research gaps remain. Disturbance histories at the stand scale and attribution to disturbance type and severity remain poorly characterized, as are rates of forest conversion.

Major uncertainties

Improved estimates of the location, severity, and timing of natural disturbances are needed, particularly in Mexico. Degradation of forest stocks (e.g., from selective logging, low-severity disturbances, and stress) also remain poorly characterized at the scales needed for assessing carbon dynamics and managing forest carbon. Also needed are landscape-scale records of management practices such as replanting, selective harvesting, cyclical use, and agroforestry. Integration of a range of remote-sensing technologies, including light detection and ranging (LIDAR), with field plot data and carbon cycle modeling, promises to substantially improve the ability to measure and monitor forest carbon dynamics at large scales. Addressing these and other gaps ultimately will lead to spatially explicit estimates of carbon stocks and fluxes that comprehensively assess impacts of disturbance, management, and environmental changes on carbon fluxes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

While the evidence base strongly supports the finding of net carbon uptake by North American forests, attribution of this carbon uptake to driving factors remains less well understood. This is in part because each factor's contribution is likely to change across diverse forest settings and conditions.

Summary sentence or paragraph that integrates the above information

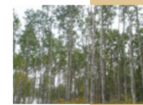
Attributing carbon fluxes in North American forests to specific natural and human activities remains a challenge given the diversity of forest types, land-use changes, disturbance dynamics, and human activities that influence these fluxes.

KEY FINDING 3

Annual harvest removals from forestry operations in select regions decrease forest carbon stocks, but this decline in stocks is balanced by post-harvest recovery and regrowth in forestlands that were harvested in prior years. Removal, processing, and use of harvested biomass causes carbon emissions outside of forests, offsetting a substantial portion (about half) of the net carbon sink in North American forests (*high confidence*).

Description of evidence base

Recent trends in natural disturbance rates indicate that the strength of net forest uptake has diminished across much of North America. Net loss of forest carbon stocks from land conversions also reduces sink strength across the continent, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation. These findings are supported by 1) national inventory reports of greenhouse gas emissions and removals in the forestland category in Canada (ECCC 2016), Mexico (INECC/SEMARNAT 2015), and the United States (U.S. EPA 2018); 2) atmospheric inversion models (Peylin et al., 2013); 3) syntheses of forest inventory and land-change data (Pan et al., 2011); 4) measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010); and 5) ecosystem process models (Sitch et al., 2015).



Major uncertainties

Intensively managed forests are among the most well understood ecosystems in North America. Decomposition dynamics associated with harvested wood products are less well understood, however, and changes in forest use and climate may alter these dynamics in the future. Furthermore, basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The carbon balance impacts of harvesting are well observed and well understood thanks to a wide range of observations that are compiled, analyzed, and reported in detailed accounts.

Summary sentence or paragraph that integrates the above information

Intensive forest management in select regions is widely known to cause large annual reductions in forest carbon stocks. Less understood is how forest regrowth (which often takes decades) compensates for these losses.

KEY FINDING 4

Recent trends in some disturbance rates (e.g., wildfires and insects) have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions reduced sink strength across the continent by 11 Tg C per year, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation (*medium confidence*).

Description of evidence base

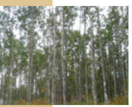
Carbon impacts of disturbance vary with several key features, including disturbance type and severity, temporal sequence of events, and biotic and climatic conditions of forest regeneration (Hicke et al., 2012; Williams et al., 2016). The extent, severity, and frequency of natural disturbances have increased in recent decades (Allen et al., 2010; Hicke et al., 2013), likely influenced by recent climate change and human activities.

Major uncertainties

Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Patterns and trends of major disturbances and forest conversions are well documented, however, their effects on carbon uptake and release can be diverse, presenting a significant challenge for assessing impacts on the carbon cycle.



Summary sentence or paragraph that integrates the above information

Detection and quantification of natural disturbance and land-use change in forest ecosystems have improved over the last decade. However, basic understanding of carbon dynamics following these events is still limited. Nevertheless, evidence suggests that recent trends in natural disturbance rates have diminished the strength of net forest uptake across much of North America.

KEY FINDING 5

Several factors driving the carbon sink in North American forests are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake (*medium confidence*).

Description of evidence base

Accounting for land-use change, management, disturbance, and forest aging, U.S. forests are projected to continue to uptake carbon but at declining rates, largely because of land-use dynamics and aging forests (USDA-OCE 2016; Wear and Coulston 2015). After 20 years of net gains, forest area is projected to level and then decline gradually after 2030 because of ongoing population growth and declining afforestation on agricultural lands (U.S. Forest Service 2012; Wear and Coulston 2015). In the western United States, aging forests coupled with disturbance dynamics are projected to diminish carbon uptake to negligible levels by midcentury. Younger productive forests in the East are expected to take up atmospheric carbon at a high rate, though harvest-related emissions substantially reduce the net effect on atmospheric carbon.

Major uncertainties

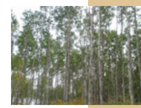
Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predicting disturbance trends into the future is challenging because of limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging. Forest regrowth following historical clearing plays a role, but studies also suggest sizeable contributions from growth enhancements such as CO_2 fertilization, nitrogen deposition, or climate trends supporting accelerated growth. Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Although projections vary depending on future climate and land-use scenarios, theory, observations, and modeling all support the expectation that today's carbon uptake from aging forests and from forest expansion will begin to decline in coming decades, and that natural disturbances will become more frequent and severe, releasing more forest carbon to the atmosphere.

Summary sentence or paragraph that integrates the above information

Although detection and quantification of natural disturbance and land-use change in forest ecosystems have improved over the last decade, basic understanding of carbon dynamics following these events is still limited. Several factors driving the forest carbon sink are expected to decline over coming decades, and although predicting disturbance trends into the future is challenging, an increasing rate of natural disturbance could further diminish the current estimated net carbon uptake by North American forests.



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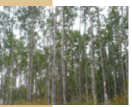

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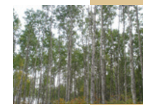

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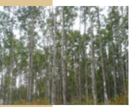

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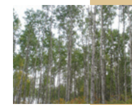

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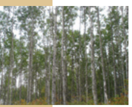

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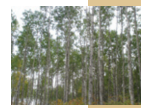

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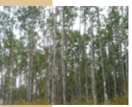

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