

Chapter 6

Boreal forests

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1 Carbon in boreal forests

The boreal forest is one of the largest biomes on Earth, occurring in the northern high latitude regions mostly between about 50°N and 65°N (Fig. 1). The biome is dominated by coniferous trees, often occurring as extensive areas of pure-species, even-aged stands regenerated from large, stand-replacing disturbances. Its northern extent lies along the tundra-taiga ecotone; on its southern extent, boreal forest types begin to transition to more temperate conifer species and a greater mix of hardwoods (Goldblum & Rigg, 2010; Montesano, Neigh, Macander, Feng, & Noojipady, 2020). Natural disturbances are a prominent feature of the boreal forest, with high severity fires and insect outbreaks occurring on relatively frequent cycles (Angelstam & Kuuluvainen, 2004; Cogbill, 2007) over a range of spatial scales (Gromtsev, 2002; Hunter, 1993; Kasischke et al., 2010a, 2010b, 2010c; Taylor, Carroll, Alfaro, & Safranyik, 2006; Weed, Ayres, & Hicke, 2013). Changes in these natural disturbance regimes—including fire, insect outbreaks, storms, and drought—will play a large role in the future carbon budget of the boreal forest (Kasischke et al., 2010a, 2010b, 2010c; Navarro, Morin, Bergeron, & Girona, 2018).

A variety of terrain and ecosystem types create a diversity of hydrologic systems, from fast-flowing rivers in steep terrain to flat, poorly drained landscapes with numerous lakes and wetlands. The boreal forest region gives rise to several very large rivers that drain extensive watersheds and often include substantial delta systems at their confluence. Soils vary across the region according to climate, substrate, forest type, landscape position, and drainage pattern (Kuhry et al., 2013). Permafrost-affected landscapes are an important feature of the

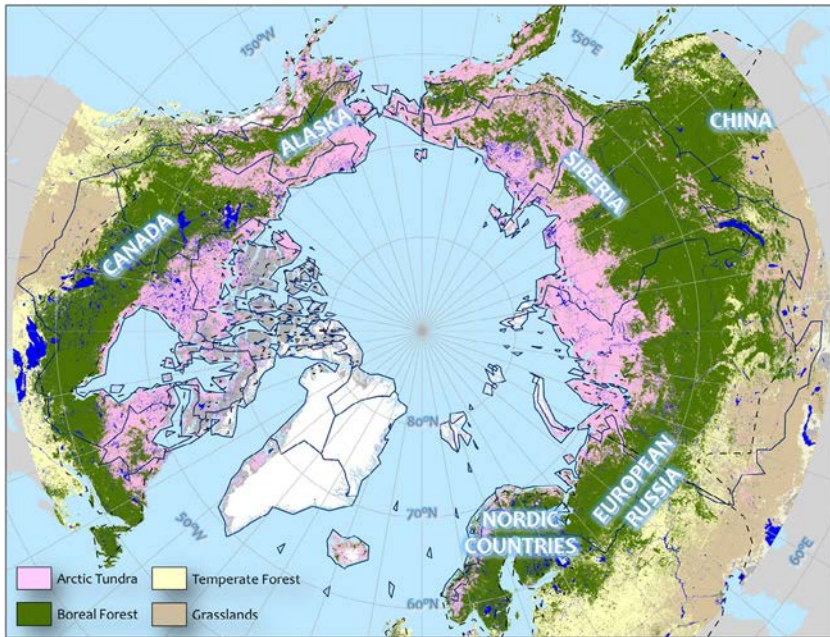


FIG. 1 The geographic scope of this chapter follows the distribution of the boreal forest biome across the circumpolar northern high latitudes. The boreal forest is mostly located between 50°N and 65°N latitude, bordered by grasslands or temperate forest to the south and arctic tundra to the north. This domain encompasses several major regions discussed in this chapter—including the Nordic countries (Norway, Sweden, and Finland), European and Siberian Russia, China, Alaska, and Canada—where national forest inventories and other “bottom-up” budgets are typically conducted. The boreal forest is contained within three “Transcom” regions that have typically served as the boundaries (dotted lines) for large-scale atmospheric inversion modeling and “top-down” constraints in model-data comparison studies of land-atmosphere carbon exchange (McGuire et al., 2012). The solid blue lines represent the boundaries of the major watersheds of the Arctic Basin, within which most of the boreal forest is contained and where the lateral export of carbon through the river systems can be monitored as the “sideways” constraints on regional budgets. (Modified from Hayes, D. J., McGuire, A. D., Kicklighter, D. W., Gurney, K. R., Burnside, T. J., & Melillo, J. M. (2011). *Is the northern high-latitude land-based CO₂ sink weakening?* *Global Biogeochemical Cycles* <https://doi.org/10.1029/2010GB003813>.)

boreal forest, covering about 80% of the region (Helbig et al., 2016; Zhang, Barry, Knowles, Heginbottom, & Brown, 2008). The current and future trajectories in ecosystem composition, structure, and function across the boreal forest are determined by complex interactions and feedbacks among climate warming, wildfire, hydrology, and permafrost thaw (Baltzer, Veness, Chasmer, Sniderhan, & Quinton, 2014; Carpino, Berg, Quinton, & Adams, 2018).

The boreal forest region mainly spans eight nations. Canada, the Nordic countries (Norway, Sweden, and Finland), and Russia make up the core of this region, and the vast majority of the forest of these nations is considered to be of the boreal type. The United States, in Alaska, and China, in its northeastern

region, both contain significant areas of boreal forest. Boreal forests are also found in smaller areas of Southern Greenland, Iceland, and the Faroe Islands. Compared to other global regions, the boreal forest shows a relatively small footprint of direct human development, limited to a few centers of urban, agricultural, and resource extraction land uses. The area of boreal forest has remained relatively stable in recent decades, compared to the greater amounts of forest land cover and land-use change found in the temperate and tropical biomes (Pan et al., 2011). Despite the low population density across the boreal region, about two-thirds of its area is under some form of management, primarily for the harvesting of wood (Gauthier, Bernier, Kuuluvainen, Shvidenko, & Schepaschenko, 2015; Saucier, Baldwin, Krestov, & Jorgenson, 2015). The Nordic countries have a highly mechanized and efficient forest industry. Large portions of the Canadian and Western Russian boreal forest are also under active management, whereas expansive regions of Alaska, Northwestern Canada, and Siberia remain largely unmanaged with limited commercial forestry or wood harvesting.

1.1 The major components of the boreal forest carbon budget

The boreal forest region acts as a net source of greenhouse gases to the atmosphere through emissions primarily from fossil fuel combustion, biomass burning in wildfire, and outgassing from inland waters and wetland ecosystems (Le Quéré et al., 2017; Pastor et al., 2003; Price et al., 2013; Saunois, Jackson, Bousquet, Poulter, & Canadell, 2016). Fossil fuel emissions are tracked and reported at national levels and so do not necessarily follow the borders of the boreal region itself. Excluding the United States and China, the core boreal countries have accounted for around 10% of global emissions, and this proportion has been declining over recent decades. Since 2008, the Russian Federation is ranked fourth globally in total fossil fuel emissions and Canada is ranked ninth, while Finland, Sweden, and Norway ranked 59th, 62nd, and 65th among world nations, respectively (Le Quéré et al., 2016). While the statistics are difficult to track, it is likely that a substantial portion of the carbon embedded in fossil fuels and harvested wood products originating in the boreal forest region is exported to, consumed in, and emitted from other more populated regions of the world.

Boreal forests contain substantial stocks of carbon in their ecosystems, about one-third of the global terrestrial storage total (Bradshaw & Warkentin, 2015; McGuire et al., 2009; Pan et al., 2011). Boreal forests contain about 25%–30% of the live biomass carbon of global forests, and some studies have estimated up to 60% of the soil carbon (Dixon et al., 1994; Fyles et al., 2000; Kasischke, 2000). Despite the limited vegetation productivity, carbon accumulates in boreal forest soils as the rates of organic matter decomposition are reduced by the cold and water-saturated conditions (Hobbie, Schimel, Trumbore, & Randerson, 2000). A significant portion of the total boreal forest carbon stock is found in the region's peatlands (Hugelius et al., 2014; Kasischke, 2000).

Excluding the anthropogenic source from fossil fuel combustion, the ecosystems of the boreal forest biome have long been considered to be acting as

a net sink in terms of the global terrestrial carbon cycle (Ciais et al., 2010, 2010; Goodale et al., 2002; Myneni et al., 2001). A global-scale analysis of forest inventory information shows that boreal forests as a whole had a consistent net rate of carbon accumulation in the 1990s and 2000s, accounting for 20%–22% of the global carbon sink in established forests during those decades (Pan et al., 2011). Historically, carbon accumulation in biomass has been limited by low vegetation productivity, but the relatively high rates of disturbance across the region have resulted in tree mortality and the transfer of large amounts of carbon from the live to dead organic matter pools (Kurz et al., 2008; Kurz et al., 2013; Kurz, Stinson, & Rampley, 2008; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008; Stinson et al., 2011). The combustion of biomass and organic matter from Boreal Forest vegetation and soils in wildfires makes a globally significant contribution of greenhouse gases (GHGs) to the atmosphere on an annual basis (Van Der Werf et al., 2017). The boreal region is also a major contributor to biogenic methane (CH_4) emissions at the global scale due to its extensive peatland and wetland areas and the wet, organic-rich soils commonly found in boreal forest ecosystems (McGuire et al., 2009; Roulet, Ash, & Moore, 1992). Increases in such climate- and disturbance-driven carbon losses could lead to a weakening of the boreal land sink.

The high latitudes are warming faster than anywhere else on Earth (AMAP, 2017; Gauthier et al., 2015; Serreze & Barry, 2011; Walsh, 2014), and this is driving an increase in “natural” disturbances (e.g., drought, wildfire, insect outbreaks) throughout the boreal forest region (Kasischke et al., 2010a, 2010b, 2010c; Kasischke & Turetsky, 2006; Kurz, Dymond, Stinson, Rampley, et al., 2008; Kurz, Stinson, & Rampley, 2008; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008; Turetsky et al., 2011). These factors cause ecosystem carbon losses from thawing permafrost (Hayes et al., 2014; Schuur et al., 2015) and disturbance emissions (Amiro et al., 2011; Balshi et al., 2009a, 2009b; Chen, Hayes, & David McGuire, 2017), thus leading to a weakening of the Boreal Forest sink for global atmospheric CO_2 (Hayes et al., 2011; Hayes, McGuire, Kicklighter, Burnside, & Melillo, 2011; Kurz, Dymond, Stinson, Rampley, et al., 2008; Kurz, Stinson, & Rampley, 2008; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008; Ma et al., 2012). Model projections suggest that high-latitude ecosystems could gain carbon over the next century under lesser global warming scenarios, but otherwise are likely to lose substantial amounts of carbon after the year 2100 in the absence of an aggressive climate change mitigation pathway (McGuire et al., 2018).

2 Estimating carbon stocks and fluxes in boreal forests

The overall impact of the boreal forest on the atmospheric GHG budget is determined by the imbalance between the anthropogenic and natural sources of carbon dioxide (CO_2) and CH_4 versus the carbon taken up by its natural and managed ecosystems (Fig. 2). The major, continental-scale sources of GHGs from the boreal region originate by: (1) fossil fuel combustion, (2) wildfire

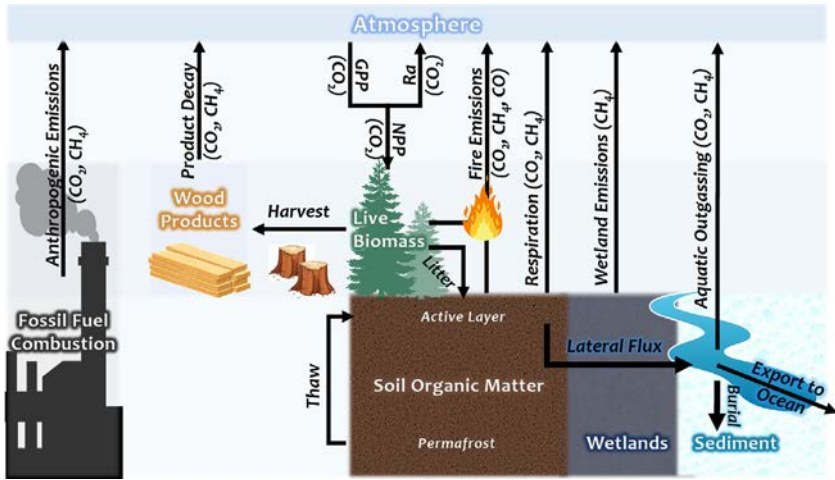


FIG. 2 Pool and flux diagram illustrating the stocks and flows among the major components of the boreal forest carbon budget. The net exchange of carbon-containing greenhouse gases (GHGs: CO_2 , CH_4 , CO) between the atmosphere and the land surface over a regional-scale domain is estimated directly using top-down approaches such as atmospheric inversion modeling. The net ecosystem exchange (NEE) of CO_2 is also estimated at local scales with tower-based, eddy-covariance measurements that are partitioned into ecosystem uptake (gross primary productivity, GPP) and ecosystem respiration (plant respiration, R_a , plus the heterotrophic respiration of dead organic matter in litter and soils). These fluxes can then be upscaled from the tower footprints ($\sim 1 \text{ km}^2$) to broader regions of the boreal forest with spatial modeling based on remote sensing. Both methods rely on observations to estimate NEE at shorter time periods (subdaily to monthly) and then are aggregated to interannual time scales over the length of the observational record. Regional-scale land-atmosphere exchange is estimated indirectly by summing across the bottom-up inventory or modeling of the major GHG source and sink components—both natural and anthropogenic—on land. Fossil fuel emissions are inventoried and reported with relatively small uncertainty at state/province to national levels. Point sources of anthropogenic GHG emissions are more difficult to track at local scales. National forest inventory (NFI) programs are typically cited as the best available information on carbon stocks and stock changes across the boreal forest domain. As a key part of these inventories in boreal forests, GHG emissions from wildfire are estimated based on aerial survey and satellite remote sensing of burned areas combined with models of fuel loads and fire behavior. While NFIs provide reliable estimates of the change in tree biomass and harvested wood product pools between two points in time from the periodic measurement of the plot networks, other pools—especially soils—are undersampled and thus more uncertain. Furthermore, large areas of the boreal forest are designated “unmanaged” and not subject to GHG reporting for international agreements and so are not included in NFIs. Other research-driven methods such as terrestrial biosphere modeling are used to fill in these gaps in undersampled pools and noninventoried geographies. There are no formal carbon inventories for nonforest ecosystems, such as peatlands and other wetlands, that cover large areas of the boreal region and emit large amounts of CH_4 to the atmosphere. These estimates can be included in the budgets based on various scaling methods from “measure-and-multiply” extrapolation of field studies to more detailed, process-based modeling. Finally, the regional budget is closed by estimating the lateral flux of terrestrial carbon to the aquatic system, the amount buried in sediments, and the outgassing of GHGs from the water column back to the atmosphere. These fluxes are typically derived from empirical estimates constrained by measurements of dissolved carbon concentrations in the water leaving stream and river systems. (Modified from McGuire, A.D., Hayes, D. J., Kicklighter, D. W., Manizza, M., Zhuang, Q., Chen, M., et al. (2010). An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus, Series B: Chemical and Physical Meteorology*, 62(5). <https://doi.org/10.1111/j.1600-0889.2010.00497.x>.)

and other disturbances, and (3) emissions from wetlands and aquatic ecosystems. These sources are partially offset by sinks in natural and managed ecosystems driven by plant photosynthesis that converts CO₂ into biomass. Carbon is then stored for a longer term in boreal forest ecosystems as live biomass and dead organic matter both above- and below-ground after losses via emissions to the atmosphere and lateral export through the aquatic system.

2.1 Sampling boreal forest carbon stocks

Basic biometric measurements, field surveys, and ground-based plot networks form the basis for “bottom-up” estimates of terrestrial ecosystem carbon stocks and stock changes (see [Chapter 3](#)). Total carbon estimation in boreal forest systems requires sampled, field-based measures of the major carbon pools in the overall budget, i.e., above- and below-ground biomass, litter and woody debris, and soil organic carbon. These measures are then summed to estimates of growing stock (i.e., volume of wood) that are then converted to live biomass using wood density and allometric equations parameterized by species group, age, site, and/or geography. Such measurement campaigns are not always consistent in methodologies or comprehensive in their sampling of the major pools, i.e., the components that are more difficult to measure such as forest floor litter, downed woody debris, and soil organic matter can be significantly under-sampled. The lack of in situ data characterizing these pools leads to large uncertainties in bottom-up budgets—particularly in the boreal region where soil carbon is the largest pool but has the most uncertain estimate.

While there has been a wealth of these data collected over the decades across representative boreal forest sites and research areas ([Gower et al., 1997](#); [Pattison et al., 2018](#); [Schulze et al., 1999](#)), they are still limited in spatial coverage of this large and mostly remote region. These research data often come from “one-off” studies that are out of date and limited in their temporal scope ([Botkin & Simpson, 1990](#); [Fisher et al., 2018a, 2018b](#); [Gower et al., 2001](#)). The amount and spatial coverage of available, field-based measurement data for boreal forest carbon stocks tend to be limited by accessibility, regional extent, and institutional investment in inventory and research. More formal forest inventories are driven by the economic value of management for wood fiber, and are not necessarily designed to produce a biome-scale GHG budget. The spatial density of data collection is highest in the Nordic countries, given their long and active history of boreal forest research combined with the smaller geographical area to cover ([Næsset et al., 2004](#)). Similarly, the interior boreal forest of Alaska is relatively well studied, whereas data become sparse in more remote and inaccessible regions. Both Canada and Russia have important research areas and inventory networks, but the sheer size of these areas results in less data coverage especially in the remote and largely “unmanaged” extents of their boreal forest ([Schimel et al., 2015](#)). These field surveys form the basis of the national forest inventories (NFIs) that vary by country in terms of their spatial coverage, sampling intensity, measured components, repeat frequency, and scaling methods.

When linked to ground-based measurements, remote sensing data collected from satellites or aircraft can expand existing plot networks and field studies over time and space. Remote sensing has been a critical tool in estimating and tracking biomass carbon over large and remote boreal forests with few and scattered field sites (Margolis et al., 2015; Neigh et al., 2013). Boreal forests have historically served as important test areas demonstrating the use of high-resolution optical sensors from low-altitude aircraft, including traditional aerial photography (Leckie & Gillis, 1995; Maclean & Martin, 1984; Magnusson, Fransson, & Olsson, 2007), digital photogrammetry (Bohlin, Wallerman, & Fransson, 2012; Næsset, 2002; White et al., 2013), and hyperspectral imaging (Halme, Pellikka, & Möttöus, 2019). Active remote sensing systems, i.e., airborne LiDAR (light detection and ranging) and synthetic aperture radar (SAR), are capable of 3D characterization of forest structure and commonly used to estimate above-ground tree biomass. The sensitivity of SAR backscatter retrievals to above-ground biomass (AGB) has been demonstrated across a range of boreal forest conditions, structures, and geographies (Neumann, Saatchi, Ulander, & Fransson, 2012; Rignot, Williams, & Viereck, 1994; Sandberg, Ulander, Fransson, Holmgren, & Le Toan, 2011).

Airborne laser scanning (ALS), or LiDAR, is considered the most promising approach for accurate, high-resolution biomass mapping (Boudreau et al., 2008; Montesano et al., 2014) in large part because of its extensive application in boreal forests, particularly in Canada (Lim, Treitz, Wulder, St-Onge, & Flood, 2003; Treitz et al., 2012) and the Nordic countries (Gobakken et al., 2012; Hyypä et al., 2008; Næsset, 2004). ALS acquisitions can be linked to plot-based inventories to map forest carbon and other management-relevant forest attributes over larger areas (White et al., 2013, 2017; Wulder et al., 2012). These small-footprint LiDAR data show accurate and consistent model results in estimating forest biomass, but with the consequence of reduced sampling area. Having few or no publicly available ALS data is a major limitation on reducing uncertainties of biomass estimates in many areas needed to capture the range of forest types over the boreal region. This is particularly pertinent in places such as Siberia and its large, remote areas of deciduous needleleaf Larch forests. Current spaceborne LiDAR assets are rapidly increasing the sampling of vegetation structure in forests worldwide. NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) is a photon-counting laser on board a polar orbiting satellite that can be used to measure forest canopy height and estimate biomass across the boreal forest biome (Narine et al., 2019; Queinnec, White, & Coops, 2021). NASA's Global Ecosystem Dynamics Investigation (GEDI) instrument is based on the International Space Station (ISS) and collects LiDAR waveforms in snapshots along its orbital track (Dubayah et al., 2020). While GEDI data are being used in spatial models to map above-ground biomass in temperate and tropical forests, the latitudinal maxima of the ISS transits at 52° north and south limits its useability for boreal forests. Near-future missions bring the promise of integrating with expanding capabilities, notably the European Space Agency's BIOMASS mission that will use satellite-based SAR to map global carbon stocks (Quegan et al., 2019).

2.2 Sampling boreal ecosystem carbon fluxes

The eddy covariance flux technique measures ecosystem-scale carbon exchange using tower-based instrumentation with footprints on the order of one or more square kilometers (Baldocchi, 2003). This technique has been applied extensively in studies of boreal forest carbon balance and variability to climate and disturbance (e.g., Barr et al., 2002; Chen et al., 1999; Grant et al., 2009; Kurbatova, Li, Varlagin, Xiao, & Vygodskaya, 2008; Lagergren et al., 2008). These net ecosystem exchange measurements are most appropriate for characterizing patterns in the biological carbon fluxes (i.e., gross primary productivity and total ecosystem respiration) over short time periods (daily to interannual) and fine spatial scales (~ 1 km). Scaling these flux measurements for regional accounting of net carbon change is a challenge, however, where a limited number of tower sites do not capture the variability known to be important in determining carbon budgets across the boreal forest domain (Chen et al., 2011; Goulden et al., 2011; Zha et al., 2013), i.e., climate and abiotic conditions, forest and other ecosystem types, and forest age and disturbance. Yet, eddy covariance flux studies have provided a wealth of understanding on the processes and controls of boreal carbon—including CO_2 and CH_4 exchange in other ecosystems such as wetlands (Rinne et al., 2007; Wang et al., 2018) and lakes (Huotari et al., 2011; Podgrajsek et al., 2016) in addition to upland forests—and thus are used as the basis for upscaling flux estimates and calibrating and evaluating ecosystem models (Clein et al., 2002; Ueyama et al., 2016; Virkkala et al., 2021).

2.3 Carbon emissions from wildfire

Disturbance, particularly fire, is a primary driver of forest carbon dynamics across the boreal region. Fire in the boreal forest is characterized by large, stand-replacing wildfires; prescribed and managed fires used for forest management or land clearing are not a significant component of the regional carbon budget. North American and Eurasian boreal fire regimes are known to be different in many ways (De Groot et al., 2013; Rogers, Soja, Goulden, & Randerson, 2015), but extensive areas of interior Alaska, Western Canada, and Siberia have been impacted by frequent, large, and severe wildfires in recent decades (Balshi et al., 2009a, 2009b; Kharuk et al., 2021; Krylov et al., 2014). Carbon losses from wildfire are often already, albeit implicitly, accounted for in the calculation of stock change between two inventory dates (Harris et al., 2016). Alternatively, fire emissions can be explicitly quantified in inventory- or process-based models by mapping burned area and estimating emissions (Chen et al., 2017; Domke et al., 2021; French et al., 2011; Van Der Werf et al., 2017).

There are various programs that actively map burned areas across the circumpolar Boreal Forest, primarily based on remote sensing. Burned area perimeters have been mapped historically from field, aerial, and satellite observations

by the Alaska Fire Service (Kasischke, Williams, & Barry, 2002). The Canadian National Fire Database maintains a collection of fire locations and burned area perimeters available since 1986 (Stocks et al., 2003) from various sources by fire management agencies among the provinces, territories, and Parks Canada. Maps of detected burn areas across the vast forests of Siberia since the 1980s have been developed by coarse resolution satellite imagery (Sukhinin et al., 2004). Burned area is currently mapped globally using Moderate Resolution Imaging Spectrometer (MODIS) data (Van Der Werf et al., 2017), which closely agrees with these other, regional data sets (Hayes, McGuire, Kicklighter, Burnside, & Melillo, 2011; Hayes, McGuire, Kicklighter, Gurney, et al., 2011). However, models using similar burned area estimates will show larger ranges in their emissions estimates due to differences in fuel loads and combustion factors. Fuel loads are determined by simulations of biomass and soil organic matter pools with a process-based ecosystem model, moderated by the proportional carbon combustion both in the above-ground vegetation as well as to some depth of the soil (Kasischke & Bruhwiler, 2002). Boreal forest fires on average tend to have a larger portion of soil carbon consumed compared to other forests (Van Der Werf et al., 2017), which results in a higher amount of smoldering relative to flaming emissions and thus releases higher CH₄ and CO emissions than other forests (French, Kasischke, & Williams, 2003).

2.4 Carbon in the aquatic system

The riverine transport of carbon from terrestrial watersheds to the world's oceans is a major component of the global carbon cycle (Li et al., 2017). While biomass stocks and land-atmosphere fluxes often receive more attention in carbon accounting, including the lateral export of carbon through the aquatic system directly impacts the estimates of carbon uptake in terrestrial ecosystems. Inland waters of the boreal forest biome in particular have some of the highest concentrations, quantities, and fluxes of dissolved organic and inorganic, and particulate, carbon (DOC, DIC, POC) (Holmes et al., 2012; Morison et al., 2012; Vonk et al., 2015). The total aquatic flux from boreal forest ecosystems is related to temperature and precipitation, river morphology, wetland, and permafrost area, among other complex factors (Laudon et al., 2011).

These land-water fluxes are critical to account for where they are otherwise assumed to be lost to the atmosphere by inventory-based assessments or stored in the ecosystem by land-atmosphere flux studies (Butman et al., 2018; Hayes & Turner, 2012). The quantities and rates of carbon transfers from land to aquatic systems remain poorly constrained spatially and are critical to properly balance inventory-based estimates of land-atmosphere fluxes. Aquatic carbon fluxes integrate landscapes within whole watersheds, from headwaters to the coast. Furthermore, carbon is produced and consumed along the length of the hydrologic network thus making direct comparisons between terrestrial and aquatic carbon fluxes difficult across biomes or ecosystem types. These differences in

scale and carbon processes have created methodological challenges for integrating these two flux pathways in carbon budgets. Aquatic fluxes also integrate across ecosystem types where measured and reported within large basins that span biomes, and thus are not easily partitioned between boreal forests and arctic tundra, for example.

The export of carbon from boreal forest ecosystems occurs largely from the drainage basins of the Arctic Ocean and its marginal seas, thus representing the key connection between the terrestrial and marine carbon cycle of the Circumpolar North (McGuire et al., 2009). Estimates of riverine DOC export to the Arctic Ocean can be derived and scaled for several large watershed domains (Lammers, Shiklomanov, Vörösmarty, Fekete, & Peterson, 2001) based on empirical relationships between concentration and water discharge data collected at gauging stations at the mouths of the major arctic-boreal river systems (Manizza et al., 2009; McClelland et al., 2008). While these estimates provide a constraint on the lateral export to the ocean, it may represent only half of the total aquatic flux that also includes quantities of carbon that are outgassed from (as both CO₂ and CH₄), and buried in the sediments of, inland water bodies (Cole et al., 2007). These other flux components are often estimated based on geospatial maps to upscale sample measurements to full watersheds based on empirical relationships with the controlling factors (Stackpoole et al., 2017). Although it is highly variable by ecosystem type, DOC production can also be considered as a proportion of terrestrial inputs from primary production, which can be simulated with an ecosystem model (Genet et al., 2013).

Biogeochemical process models can incorporate DOC flux into the aquatic system as a function of decomposition in the soil pool, but they otherwise do not simulate the fate of this carbon through the inland water network (Kicklighter et al., 2013). Process model estimates can be connected with other models to simulate the atmosphere-land-ocean as a large-scale, integrated carbon budget (McGuire et al., 2010). Less attention has been given to the lateral transport of inorganic carbon, inclusive of dissolved CO₂ (Tank et al., 2012). The sources and fate of inorganic carbon integrate both the long- and short-term carbon cycles through weathering and ecosystem respiration. Chemical tracers can be used to untangle the sources of DIC, but challenges still remain in estimating the atmospheric emissions of CO₂ along riverine networks.

3 Carbon accounting in boreal forests

For the purposes of scientific study and policy analysis, carbon budget accounting is often performed at regional scales and summarized over annual to decadal time periods. Estimation of carbon stock change for accounting efforts requires repeated measures of field plots and continuous forest inventory programs at the national level. These inventories estimate the standing carbon stocks at each successive time period, tracking the change in the major above- and below-ground pools. Inventories also typically track the harvest, removal, and fate

of wood products and their emissions as part of the overall budget. National-scale forest inventories, however, are challenging to conduct and require significant resources. Indeed, there are large areas of remote and “unmanaged” boreal forest that are not included in formal inventories, and the remeasurement cycle can be too coarse to attribute fine-scale process. Here, remote sensing and other scaling approaches can be used to help fill in these spatial and temporal gaps in carbon budget accounting.

3.1 National forest inventories

Most countries in the temperate and boreal biomes have established national forest inventory (NFI) programs with repeated measurement of permanent sample plots (Pan et al., 2011). In the 1920s, the first sample-based NFIs were established in the boreal forest—in Norway, Finland, and Sweden (Tomppo, Gschwantner, Lawrence, & McRoberts, 2010). Most modern-day NFIs in the boreal forest and elsewhere are based on statistical sampling methods where plots are randomly or systematically located across all forested areas of the country, or at least the managed portions (McRoberts, Tomppo, & Næsset, 2010). A census of the trees are made at each plot along with various measurements of each including species, diameter, height, and condition that can then be used in allometric equations to estimate tree biomass (Xing et al., 2019). Additional measurements are taken at each or a subset of the plots to estimate plot-level carbon by including other important pools such as understory vegetation, woody debris, litter, and soils (Banfield, Bhatti, Jiang, & Apps, 2002; Shaw et al., 2014). The plot-based carbon estimates are then scaled up to the national level by some type of modeling approach, which differs across the NFIs of different countries (Kurz et al., 2013; Woodall, Heath, Domke, & Nichols, 2011). Estimates of total forest carbon for the full inventoried domain can be imputed over the plot network (Wilson, Woodall, & Griffith, 2013), often making use of remote sensing and spatial modeling (Beaudoin et al., 2014; Kangas et al., 2018).

Changes in the stocks of live and dead organic matter pools in the forest are determined from NFIs by direct plot remeasurement and/or with some combination of spatial modeling and remote sensing approaches. The “stock-change” approach used in forests of the continental US, for example, is based on the difference between complete inventories at two points in time, thus capturing the total change in ecosystem carbon (Hou et al., 2021). However, the US Forest Inventory and Analysis (FIA) program does not have the density of plots in the boreal forest of interior Alaska as it does elsewhere in the country, and therefore relies on remote sensing data to fill in the gaps (Babcock et al., 2018). In the Nordic countries, carbon stock change is estimated from the NFIs based on remeasurement of a subset of each nation’s permanent plot network on a 5-year-cycle (Kangas et al., 2018). Area-based modeling using airborne laser scanning data has become a major component of the inventories over the last decade in Norway, Finland, and Sweden (Maltamo & Packalen, 2014; Næsset, 2014).

The Russian Federation has an NFI system based on a sample of ground-based inventory plots across the country's extensive forest areas, but uncertainty arises from how current the measurements are, as well as differences in assessment methods (Shvidenko & Nilsson, 2002). Inventory-based data have been compiled for Russia in broader-scale carbon budget assessments (Pan et al., 2011) and compared with other, model-driven estimates (Dolman et al., 2012).

Alternatively, Canada's national forest carbon inventory is based on the "gain-loss" method, which starts with a complete inventory that then is updated by modeling forward the components of change, including growth, mortality, decomposition, and disturbance (Kurz et al., 2009; Stinson et al., 2011). The accounting relies heavily on empirical and observational data, including for both forest growth and yield as well as disturbance characterization and mapping. The carbon budget model ingests this information and then simulates annual carbon stock changes in forest biomass. Carbon stock changes in the dead organic matter pools are directly linked to the better-known biomass dynamics, or net primary productivity. Dead wood, litter, and soil are calculated as the mass balances from inputs (through litterfall, biomass turnover, and disturbance inputs) and losses (through decomposition, transfers by harvesting, and losses to the atmosphere during disturbances such as fire). The "gain-loss" approach has been adopted by the FIA for estimates of the managed forest land in Alaska that lack remeasurements (Domke et al., 2021).

3.2 Carbon in harvested wood products

Harvested wood products (HWPs) represent an important pool of carbon, particularly in intensively managed forests like those found in the Nordic countries and other areas of the boreal region (Triviño et al., 2015). The HWP pool must be accounted for in NFIs and other carbon budget accounting efforts as a key component due to its potential for long-term carbon sequestration as well as by replacing GHG emissions from other, nonrenewable sources (Chen, Ter-Mikaelian, Yang, & Colombo, 2018; Johnston & Radeloff, 2019; Zhang, Chen, Dias, & Yang, 2020). Forest management practices and the fate of HWP play a large role in determining whether forests overall will act as net sources or sinks of carbon (Birdsey, Pregitzer, & Lucier, 2006; Paradis, Thiffault, & Achim, 2019). Most countries, including in the Boreal region, account for carbon in HWP using simple spreadsheet models, which have default assumptions for inputs to short- and long-term product pools (Bergman, Puettmann, Taylor, & Skog, 2014; Jasinevičius, Lindner, Pingoud, & Tykkylainen, 2015; Skog, Pingoud, & Smith, 2004). Some portion of the carbon removed in harvest, about 20%–40% (Hayes et al., 2012; Smith, Heath, Skog, & Birdsey, 2006), is emitted during processing into wood products. This processing, or "primary consumption," is assumed to occur largely at the mill. The remainder is assigned to an "in use" product pool of various half-life (e.g., pulp and paper vs sawlogs), solid-waste disposal (i.e., landfills),

or exported out of the country or reporting zone. Carbon is emitted as ‘secondary consumption’ from each of these pools as it decays at a certain percent over some time frame, typically calculated as a constant proportion per year over 10–100 years. For the purposes of reporting to the United Nations Framework Convention on Climate Change (UNFCCC), the International Panel on Climate Change (IPCC) recommends calculations based on the “production approach” where the carbon emissions from the decay of HWP stocks are accounted for in the country or reporting zone where the wood was originally grown and harvested, regardless of the locations of eventual primary and secondary consumption of the products (Buendia et al., 2019; Penman, Gytarsky, Hiraishi, Irving, & Krug, 2006).

3.3 Managed vs unmanaged forest lands

There are large areas of the boreal Forest where resources for NFIs are not cost-effective, prioritized, or practical. These areas are typically remote and largely unaffected in a significant way by direct anthropogenic activities such as land-use conversion, harvest, or fire suppression (Ogle et al., 2018). Approximately 51 and 118 million hectares are designated as “Unmanaged Forest Lands” in Alaska and Canada, respectively (Kurz et al., 2018; Pan et al., 2011; Fig. 3). While the US FIA program covers the coastal temperate forests of Southeast Alaska, the boreal forests of the interior are not currently included in the

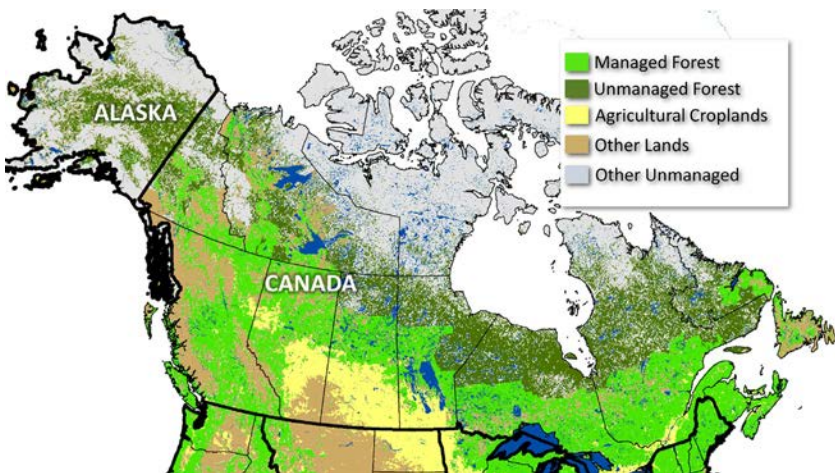


FIG. 3 Map of the managed versus unmanaged forest areas as designated in Canada and Alaska. (Modified from Hayes, D. J., Vargas, R., Alin, S.R., Conant, R. T., Hutyra, L. R., Jacobson, A. R., et al. (2018). Chapter 2: The North American carbon budget. In N. Cavallaro, G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, & Z. Zhu (Eds.), *Second state of the carbon cycle report (SOCCR2): A sustained assessment report* (pp. 71–108). Washington, DC: U.S. Global Change Research Program. <https://doi.org/10.7930/SOCCR2.2018.Ch2>.)

inventory. The criteria for, and proportion of, managed forest across Canada varies by province but are generally determined by those areas designated for timber harvesting and/or fire suppression (Kurz et al., 2009). In Alaska, new inventory plots are being installed in interior boreal forests over a 15-year period, and supplemented by advanced remote sensing data and spatial modeling techniques (Andersen et al., 2015; Babcock et al., 2018). While not reported in its national GHG inventory, unmanaged forests are included in Canada's deforestation monitoring program to track resource extraction and land-use change in order to update its land designations (Dyk, Leckie, Tinis, & Ortlepp, 2015).

Carbon sources and sinks in these unmanaged forests are dominated by the cycles of growth, succession, and natural disturbances. For example, studies show declines in the growth and high fire losses in unmanaged larch forests across the permafrost zone in Siberia (Kharuk et al., 2019; Kharuk et al., 2021). In lieu of inventories, process-based modeling can be calibrated to available ground data and used to simulate these ecosystem dynamics. Modeling studies suggest that these areas have operated as a small carbon sink in recent decades (McGuire et al., 2009) although that near-balance may be tipping toward increasing sources from wildfire (Hayes, McGuire, Kicklighter, Burnside, & Melillo, 2011; Hayes, McGuire, Kicklighter, Gurney, et al., 2011; Walker et al., 2019) and permafrost thaw (Hayes et al., 2014). Compared to the large carbon sink estimated in forests of European Russia, the boreal forests of North America are thought to be only small sinks or sources (Pan et al., 2011). As such, it is generally assumed in carbon budget assessments would not significantly change the estimates currently reported by the national-level inventories of the boreal countries (Pan et al., 2011).

3.4 The role of remote sensing in boreal forest inventories

Spatial statistical models take in situ measurements from representative locations and fill in spatial gaps by connecting them to wall-to-wall maps of environmental variables derived from remote sensing (Jung et al., 2020; Tramontana et al., 2016). Multitemporal remote sensing plays an important role in Boreal Forest inventory updates. The availability of global satellite optical, SAR, and LiDAR data—linked to ground measurements—has led to the development of wall-to-wall, regional, and circumboreal maps of AGB (Matasci et al., 2018; Neigh et al., 2013; Santoro et al., 2015). Of course, remote sensing approaches by nature are most effective at estimating above-ground carbon pools, i.e., AGB. Below-ground and other nonliving carbon pools are more difficult to estimate with remote sensing as well as in the field, and thus are often undersampled in inventories compared to live tree biomass. As such, field and remotely sensed data need to be integrated with other flux measurements and modeling frameworks (Hopkinson et al., 2016; Kimball, Keyser, Running, & Saatchi, 2000; Liu, Chen, Cihlar, & Park, 1997; Sitch et al., 2007) in order to account for a more comprehensive budget of regional-scale boreal forest carbon stock changes over time.

4 Regional-scale modeling

In order to expand the sampling of fine-scale measurements and observations to the broader scope of time and space required for regional budgets, some type of scaling approach is required. Scaling involves extrapolation of both the sample data and the understanding of fine-scale mechanisms across a hierarchy of coarser levels. Various modeling frameworks have been designed to temporally extrapolate sample flux measurements using diagnostic (Rödenbeck, Zaehle, Keeling, & Heimann, 2018) and prognostic (McGuire et al., 2016) approaches. The surface-atmosphere exchange of trace gases can be estimated essentially by two complementary approaches, using what are generally categorized as either “top-down” or “bottom-up” methodologies (McGuire et al., 2012). Top-down estimates of CO₂ or CH₄ flux are based on measurements of these trace gas concentrations from networks of atmospheric monitoring stations. Atmospheric inversion models (AIMs) use initial estimates of the land flux combined with an atmospheric transport model, then adjust the pattern of land fluxes until inferred gas concentrations closely match observations to achieve an optimized posterior flux estimate (Chen, Chen, & Worthy, 2005; Ciais, Canadell, et al., 2010; Ciais, Rayner, et al., 2010). Bottom-up models rely on ground-based, in situ measurements of carbon stocks and fluxes at representative locations to calibrate terrestrial biosphere models (TBMs). These ecosystem process simulations can be extrapolated to regional carbon budget estimates using maps of plant functional types and analyzed or predicted over time using climate, disturbance, and other forcing data (Fisher et al., 2014; Fisher, Huntzinger, Schwalm, & Sitch, 2014).

Atmosphere-based approaches are useful as a top-down constraint on regional carbon budgets because they estimate the total net surface-atmosphere exchange of CO₂ or CH₄ directly as one integrated flux. Furthermore, AIM is currently the only methodology that fully integrates aquatic contributions to atmospheric carbon, albeit with limited ability to differentiate between terrestrial and aquatic sources. However, there are large uncertainties in AIM estimates over the high latitudes that arise from the sparse observation network, transport model error, and incorrect boundary conditions (Dargaville, Baker, Rödenbeck, Rayner, & Ciais, 2006). AIMs have tended to estimate much larger carbon sinks over the boreal regions than the inventories or TBMs (Dargaville et al., 2002; Hayes, McGuire, Kicklighter, Burnside, & Melillo, 2011; Hayes, McGuire, Kicklighter, Gurney, et al., 2011). Analyses that have incorporated improvements on these data and modeling methods show that carbon uptake by boreal forests is not as strong as suggested by previous studies (Stephens et al., 2007). Regional inversions over the boreal biome do show increases in both the seasonal cycle of CO₂ exchange (Forkel et al., 2016) and the interannual net uptake of carbon in these ecosystems (Welp et al., 2016). There are uncertainties in these assessments that are associated with the role of increasing active layer depths and its impact on soil carbon respiration (Carvalhais et al., 2014). AIM results are shown to be consistent with satellite remote sensing

observations of “greening” (Beck & Goetz, 2011), despite increasing fire over many areas and browning trends in some (Verbyla, 2011). An atmospheric inversion study of CH₄ fluxes in the northern high latitudes shows positive trends in emissions from both natural (wetlands) and anthropogenic (oil and gas development) sources across the boreal region (Thompson et al., 2017). Overall, top-down modeling frameworks continue to improve their capabilities for reducing uncertainties in increasingly regional-scale estimates of land-atmosphere carbon exchange (Jacobson et al., 2018). These improvements are being driven by advances in statistical upscaling and machine-learning approaches based on rapidly increasing atmospheric GHG observations from aircraft and satellites.

Simulation experiments with TBMs allow scientists to explore hypotheses related to driver sensitivity and attribution of carbon dynamics in boreal forests and other ecosystems (Amthor et al., 2001; McGuire et al., 2001). TBMs have been applied to carbon budget estimation in boreal forests, including the impacts of climate, CO₂ fertilization, nutrient dynamics, disturbance, vegetation shifts, and land use (Euskirchen, McGuire, Chapin, Yi, & Thompson, 2009; Hayes, McGuire, Kicklighter, Burnside, & Melillo, 2011; Hayes, McGuire, Kicklighter, Gurney, et al., 2011; Kallioikoski, Mäkelä, Fronzek, Minunno, & Peltoniemi, 2018; Mekonnen, Riley, Randerson, Grant, & Rogers, 2019). Comparisons among TBM ensembles can show considerable disagreement in carbon budget estimates for both current (Fisher, Huntzinger, et al., 2014; Fisher, Sikka, et al., 2014) and future conditions (McGuire et al., 2018). These results highlight the need for TBMs to improve the representation of key, boreal-specific processes such as wildfire and permafrost dynamics (Horvath et al., 2021; Koven, Riley, & Stern, 2013; Wang, Baccini, Farina, Randerson, & Friedl, 2021) along with the high-quality in situ and remotely sensed data sets needed for benchmarking (Fisher et al., 2018a, 2018b; Stofferahn et al., 2019). Importantly, TBMs need to tackle challenging issues of scale, particularly in capturing the high subgrid heterogeneity of structure and processes in boreal forest ecosystems. TBM frameworks are increasingly working toward the development and application of individual-based models that incorporate tree and plant demography and dynamics in boreal ecosystems. Furthermore, grid-designed TBMs are not based along hydrologic networks, so additional model development is needed to properly integrate land-water transfers of carbon.

5 Synthesis

The circumboreal biome is large, remote, and relatively unmanaged compared to other, more densely populated regions of the world. However, the region's carbon budget is highly dynamic as driven by variability in climate, disturbance, and land use (Schuur, McGuire, Romanovsky, Schädel, & Mack, 2018). Despite the lower population density of this large region, the boreal nations together

account for a significant portion of global fossil fuel emissions. Deforestation is not as prevalent in the boreal region as it is in temperate and tropical forests, but there are large sources of carbon from wildfire and other disturbances along with emissions from lakes and wetlands, including as CH₄. Some portion of these carbon emissions are offset by natural sinks in boreal forest ecosystems, which can store large quantities in its vegetation and, especially, soils. Rates of carbon uptake by these ecosystems are slow, however, due to short growing seasons, cold and wet conditions, and unproductive tree species. Frequent disturbances directly and immediately emit GHGs to the atmosphere and transfer carbon to dead organic matter pools (Kurz et al., 2013) while also resulting in the suppression of the long-term biomass carbon sink (Wang et al., 2021). Forest management in the boreal region results in a substantial portion of carbon removed from the forest and stored in long-term wood product pools (Stinson et al., 2011). Considering all of these dynamics, the boreal carbon sink is relatively stable overall as a result of a loss of uptake in biomass of Canada's forests offset by an increased carbon sink in the other boreal regions (Pan et al., 2011).

There is large uncertainty around how the boreal carbon cycle will respond to future changes (Kurz, Dymond, Stinson, Rampley, et al., 2008; Kurz, Stinson, & Rampley, 2008; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008), and so it is critical that all of these various dynamics are carefully and consistently accounted for in both scientific assessments and GHG inventory reporting. Toward this end, there are many field studies and research networks across the boreal region that provide in situ data on forest carbon stocks. These data have been used to extrapolate carbon budget information over larger regions by their use in calibrating and validating remote sensing and process-based models. Relative to other large regions, boreal forest carbon resources are well inventoried, with Canada, Russia, and the Nordic countries, all having formal NFIs that form the basis for their GHG reporting from the land use sector. Despite this existing information and accounting tools, there remain challenges in representing all of the geographies and carbon pools of such a large domain. There are pools and fluxes that are undersampled in these inventories, and the global land surface models are missing many of the boreal-specific mechanisms altogether. In particular, model comparison studies have shown large uncertainty in the simulation of soil carbon stocks in high-latitude ecosystems, largely a function of differing initial conditions (Huntzinger et al., 2020). There are many opportunities to improve carbon data and accounting in boreal forests coming online, including programs being developed that link inventory with remote sensing and modeling for noninventoried forests such as in Alaska and Northern Canada.

The calculation of the contribution of forest carbon to net-zero emissions targets is complicated by the managed land proxy used for national GHG reporting (Grassi et al., 2021). Countries only get "credit" for these offsets in their managed lands, but in many nations substantial areas of boreal forest are

considered “unmanaged” because there is no evidence that direct human intervention has influenced its condition (Ogle & Kurz, 2021). Defining the land base for what is “managed forest” and thus included in GHG reporting will have implications for policy actions to mitigate GHG emissions (Grassi et al., 2017). The IPCC provides guidelines for how countries may define what is “managed” versus “unmanaged” lands for the purposes of UNFCCC reporting (IPCC, 2010), a distinction adopted by the United States and Canada. With respect to scientific assessments more generally, the distinction is made more about whether or not forest areas are regularly and comprehensively inventoried. Indeed, large areas of unmanaged forests in the boreal region lack sufficient ground data and reporting information for the level of carbon accounting that is consistent with the other forestland areas that are included in the NFIs. These unmanaged, or noninventoried, forest areas are not included in national GHG reporting, which results in a significant discrepancy with estimates of forest-based sinks from global models.

While carbon sources and sinks in forests and other lands are directly impacted by anthropogenic management, they are also a function of “natural” processes of the ecosystem (Ogle et al., 2018). National GHG inventories focus on anthropogenic sources because policy interventions and active management can directly influence emissions and offsets. However, other nonanthropogenic carbon sources are significant in the boreal region as a result of prevalent disturbances such as wildfire and insect outbreaks. There are also important, but uncertain, emissions from other wetland and permafrost ecosystems that are not likely to be impacted by direct management actions. Solutions to this discrepancy in attributing anthropogenic versus natural impacts on GHG emissions and offsets involve alternative approaches that can isolate and quantify the impacts of management on the forest carbon budget from those sources and sinks controlled by disturbances and natural processes (Grassi et al., 2018; Kurz et al., 2018).

From a scientific perspective, confidence in the estimates of regional-scale carbon budgets is expected to increase in the near future with more observations, improved data, and better understanding of the processes. Atmospheric models such as NOAA’s CarbonTracker system are increasingly being constrained by regional atmospheric inversions with greater numbers of observations. Aided by focused field and airborne data campaigns like NASA’s Arctic-Boreal Vulnerability Experiment, TBMs are being developed and tested to incorporate key ecosystem processes needed to better simulate boreal forest carbon dynamics (Fisher et al., 2018a, 2018b). Although there is value in comparing the various top-down and bottom-up approaches for estimating and carbon fluxes, the greatest progress can be made by integrating them more formally in accounting frameworks (Hayes et al., 2018). Meanwhile, NFI programs of the boreal countries will continue to provide high-quality, ground-based, and updated information on carbon stocks across the region. Much of the leading edge of research on remote sensing for forest inventory is being demonstrated in boreal forests (White, Chen, Woods, Low, & Nasonova, 2019; Wulder, Bater,

Coops, Hilker, & White, 2008), and new data and tools such as spaceborne LiDAR are becoming increasingly available for this work (Popescu et al., 2018). Future space-based remote sensing observations hold promise for the development of a continuous monitoring system comprehensive of the key components of the boreal forest carbon cycle (Duncan et al., 2020).

All of these regional-scale inventory, modeling, and accounting approaches discussed in this chapter will be needed to fill in reporting gaps in noninventoried lands and undersampled components of the boreal forest carbon budget, with careful attention to the consistency and compatibility of these scientific assessments with the policy requirements of GHG reporting. As the scientific community continues to refine methodologies to quantify, monitor, and predict changes in carbon storage and flux across the boreal region, new insights and approaches are needed that acknowledge natural systems as continuums, without discrete boundaries, and where the flows of carbon are highly connected. Forest inventory, remote sensing, and modeling approaches have traditionally discretized landscapes as our understanding of individual ecosystems has evolved. This partitioning of landscapes is used as the framework for GHG accounting and reporting as it provides pathways for management decisions to be implemented. However, as changes in climate disproportionately impact large regions of the boreal forest, many of our traditional definitions of ecosystems may change as well. Carbon budgets and GHG accounting systems will thus require methodology and modeling frameworks to be flexible into the future, including the incorporation of growing observation networks and new data streams.

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