Quantifying the impacts of human activities on reported greenhouse gas emissions and removals in Canada’s managed forest: conceptual framework and implementation

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Abstract: The land sector is expected to contribute to strategies aimed at mitigating global temperature increases and this necessitates an improved understanding of human actions on land sector emissions and removals. Current Intergovernmental Panel on Climate Change guidelines for the land sector of national greenhouse gas inventories are based on the assumption that all emissions and removals in managed lands are caused by humans. In Canada, however, natural disturbances in managed forests can result in large and highly variable emissions and subsequent removals that mask the impacts of management activities. Here we describe methods to isolate and quantify the impacts of management on trends in estimated anthropogenic emissions and removals in Canada’s managed forest by partitioning fluxes from two land components: fluxes from lands dominated by natural disturbance effects and fluxes from the remaining managed forests. The sum of the flux estimates of the two land components is equal to net emissions and removals in managed forest lands. Separating highly variable natural disturbance fluxes from the remaining fluxes in managed forest lands increases the understanding of how human activities impact flux trends. Comparing these anthropogenic emissions and removals with those from natural disturbances quantifies their relative contributions to global atmospheric CO₂ concentrations.

Key words: carbon, greenhouse gas inventory, anthropogenic, managed forest, climate change mitigation, CBM-CFS3.

1. Introduction

The purpose of the annual reporting of national anthropogenic greenhouse gas (GHG) emission and removal estimates to the United Nations Framework Convention on Climate Change (UNFCCC) is to quantify the impacts of human activities on the atmosphere, understand the main drivers of these emissions, inform mitigation policies, and quantify the changes resulting from climate change mitigation activities. In the land use, land-use change, and forestry (LULUCF) sector, the net balance of emissions and removals is strongly affected by both human and natural drivers, and their relative contribution to totals is difficult to quantify (Intergovernmental Panel on Climate Change (IPCC) 2003; Canadell et al. 2007; Kurz 2010). In 2003, the IPCC concluded that “The scientific community cannot currently provide a practicable methodology [to] factor out direct human-induced effects from indirect human-induced and natural effects for any broad range of LULUCF activities and cir-
cumstances” (IPCC 2003a). The IPCC introduced the Managed Land Proxy (MLP) as a default approach, which requires that all emissions and removals from managed lands be reported and attributed to human activities (IPCC 2003b).

However, in countries with large areas affected by natural disturbances such as Canada (Kurz et al. 2008a, 2008b; Stinson et al. 2011), Russia (Shvidenko and Nilsson 2002), and Australia (Richards and Evans 2004), estimates reported using the MLP approach can be strongly affected by natural disturbances. Both the variability and the trends in GHG fluxes are predominantly due to wildfire and periodic outbreaks of forest insects, masking the impacts of changes in human activities on the net GHG contribution of the forest sector (Environment and Climate Change Canada 2016). In Canada, net forest land emissions and removals are highly variable over the reporting period due to variations in the annual area burned (Stinson et al. 2011; Metsaranta et al. 2017). Between 1990 and 2016, wildfires have contributed annual direct emissions of between 11 and 242 megatonnes of CO₂ equivalents per year (Mt CO₂e-year⁻¹).

Several possible approaches to separating anthropogenic and natural emissions have been evaluated (IPCC 2010). However, it was concluded that “[d]espite valid concerns, the managed land proxy remains a globally applicable, assessed and approved method for separating anthropogenic emissions and removals” (IPCC 2010: 19) and that further scientific work on this issue could lead to more mature approaches.

Given the difficulty in developing alternative default approaches, reporting guidelines for national GHG inventories encourages countries to refine LULUCF estimates through the application of country-specific approaches. These methodologies must be scientifically based, transparently documented, and compatible with principles in the IPCC 2006 guidelines (UNFCCC 2013). Various countries have developed methods to refine estimates of anthropogenic emissions and removals in the LULUCF sector that better reflect national circumstances. For example, a modelling approach was developed for Australia’s GHG inventory to identify and separate anthropogenic and natural disturbance such as wildfires (Government of Australia 2018).

Here, we propose and implement an approach for Canada’s managed forest and show that it better reflects the impacts of human activities and forest land management on the magnitude and trends of GHG emissions and removals in Canada’s managed forests, as reported in Canada’s GHG inventory. The approach is based on separating fluxes from stands whose carbon dynamics are dominated by the impacts of natural disturbances from all remaining stands in the managed forest. This new approach is designed to more accurately represent the GHG impacts of forest-sector management and climate change mitigation activities. The analysis was implemented and carried out using Canada’s National Forest Carbon Monitoring, Accounting and Reporting System (Kurz and Apps 2006; Stinson et al. 2011; Metsaranta et al. 2017) with data reported in Canada’s 2018 national GHG inventory (Environment and Climate Change Canada 2018).

2. Methods

2.1. Canada’s National Forest Carbon Monitoring Accounting and Reporting System

Canada’s National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS; Kurz and Apps 2006; Stinson et al. 2011; Metsaranta et al. 2017) has been developed to meet requirements under the UNFCCC. It uses a spatially referenced tier 3 approach based on the IPCC gain-loss method, which uses activity data on human activities and natural disturbances to model carbon dynamics in Canada’s managed forest. Canada’s managed forests include areas under forest management, areas with intensive protection from natural disturbances, and protected areas such as parks (Stinson et al. 2011; Ogle et al. 2018). A separate module tracks the fate of biomass transferred through harvest from ecosystems to the forest product sector and reports on harvested wood product (HWP) carbon stock changes and emissions. Estimates of GHG emissions and removals are reported at the spatial scale of reporting zones, which are essentially Canada’s terrestrial ecosystems, with some ecozones further divided into east and west regions (Boreal Shield and Taiga Shield) and semi-arid and subhumid areas for the Prairies ecozone (Environment and Climate Change Canada 2018; see Supplementary Fig. S1).

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz and Apps 1999; Kurz et al. 2009; Kull et al. 2016) is the core ecosystem model of the NFCMARS. The model is widely used in Canada (Kurz et al. 2008a, 2008b; Metsaranta et al. 2011; Smyth et al. 2014) and internationally (Pilli et al. 2013, 2016a, 2016b; Kim et al. 2016). It has been extensively evaluated against ground plot observations (Shaw et al. 2014) and thoroughly evaluated with respect to model uncertainties (Metsaranta et al. 2017), potential improvements to process representation (Kurz et al. 2013), and parameter choices (Hararuk et al. 2017).

The methods, input data, and assumptions used in national-scale applications of the CBM-CFS3 have been described in detail elsewhere (Kurz and Apps 1999; Kurz et al. 2009; Stinson et al. 2011; Kull et al. 2016; Metsaranta et al. 2017), and the main points are briefly summarized in this section. Revisions to the model implemented for this study that only affect the reporting of results are described in the next section. No other aspects of the model were changed for this analysis. The CBM-CFS3 summarizes carbon dynamics in the five carbon pools defined by the IPCC but simulates the underlying dynamics in considerably more detail by tracking 11 detrital and soil carbon pools and five biomass categories (foliage, merchantable wood, other wood, and coarse and fine roots) for each a softwood and hardwood species group.

Natural disturbances such as wildfire and insect outbreaks occur over large areas of Canada’s managed forests. Given the natural disturbance history and predominantly clearcut based harvesting practices across Canada, the CBM-CFS3 assumes that stand dynamics can be represented by yield curves that depend on stand age (or more accurately time since last stand-replacing disturbance) and that stand age is set to zero following such disturbances (Kurz et al. 2009). This approach implies that forest stands are even-aged (more accurately a single cohort that has regenerated following disturbance), which is the case for the majority of stands in Canada’s managed forests. The origin of forest stands is assumed to be from either stand-replacing wildfire or harvest. Partial disturbances such as insects or thinning can also be represented in the model (Kurz et al. 2009; Pilli et al. 2013).

The main input data used by the model are forest inventories that describe the state of the forest (size, species composition, site index, etc.), empirical yield curves used to predict productivity, statistics describing the location and area of management activities and land-use change, and remote sensing and other data to determine areas affected by natural disturbances. Allometric models predict above- and below-ground biomass from wood volume (Li et al. 2003; Boudewyn et al. 2007), and process-based modelling is used to simulate the dynamics of soil and dead organic matter (DOM) carbon (Kurz et al. 2009). The model uses disturbance matrices (IPCC 2006; Kurz and Apps 1999; Kurz et al. 1992) that are specific to disturbance types to represent their impacts on the mortality of live biomass, the transfer of carbon among ecosystem carbon pools, the emissions of carbon to the atmosphere (as CO₂, CH₄, and N₂O), and the transfers of carbon to the forest.
product sector. In the case of insects, disturbances may cause only partial mortality in the year of disturbance, in addition to growth reductions that occur in the years following the disturbance, depending on the type of insect and the severity of the infestation (Kurz et al. 2008a; Dymond et al. 2010). Non-CO₂ gases are calculated in CO₂ equivalents using global warming potential values from the IPCC’s fourth assessment report (IPCC 2007). Emissions of CO₂ from the atmospheric oxidation of carbon monoxide from biomass burning are not included in the forest land estimates, as indirect CO₂ is reported in a separate table in national GHG inventories in accordance with the UNFCCC inventory reporting guidelines (UNFCCC 2013).

Many features of the CBM-CFS3 have been developed specifically to support estimation and reporting of GHG emissions and removals using methods that are compliant with the IPCC guidelines (IPCC 2006) and the reporting requirements of the UNFCCC. For reporting purposes, the NFCMARS simulates from 1990 onward and tracks all stocks and fluxes in annual time steps. Initial estimates of the carbon content in soil and DOM carbon pools are derived through a process that simulates the effects of repeated periodic stand-replacing disturbances of the last disturbance type and the time since disturbance (Kurz and Apps 1999; Kurz et al. 2009). Each of about 2.7 million stands is iterated through a process of growth and disturbance at region-specific historic disturbance return intervals, with wildfire as the typical historic disturbance type, and is terminated when the soil carbon pools at the end of two disturbance cycles are within 0.1% of each other. At that point, the model applies one more stand-replacing disturbance (harvest or wildfire) that leads to the establishment of the current stand and grows the stand to its age in 1990, obtained from the forest inventory. Carbon stocks and fluxes during the pre-1990 initialization process are not recorded; only the ending condition is tracked and used as the starting condition for the subsequent simulations.

In 1990, all stands in Canada’s managed forest are initially categorized as of either natural disturbance or harvest origin. The last stand-replacing disturbance type (harvest, wildfire) and age are in many cases available in the forest inventories for managed forest areas in Canada, and where missing, region-specific assumptions are used to assign probable last disturbance types, e.g., based on information when commercial harvest started in boreal regions of Canada. All ecosystem C pools are then loaded into the files that define the initial conditions (i.e., end of 1989) used for estimating GHG emissions and removals for the period 1990 to the most recent reporting year. This approach to initializing forest ecosystem carbon pools works generally well (Shaw et al. 2014), although many problems remain with bias in the estimation of specific pools, specific ecosystems, specific forests types, and specific soil types (Bona et al. 2013, 2016; Shaw et al. 2014; Hararuk et al. 2017).

Starting in 1990, the model simulates annually natural disturbances (e.g., wildfire, defoliating insects, bark beetles), forest management activities (clearcut harvest, partial harvest, salvage harvest, residential firewood harvest, and the burning of harvest residues), and land-use changes due to deforestation, afforestation, and reforestation. Disturbance rates are defined either as an annual area target or, for harvesting, as a volume target (expressed in units of carbon). At the national scale, the model is run in a spatially referenced mode, and therefore, rules are used to define, for each disturbance type and region, which stands are eligible for that disturbance. For example, classifiers in the inventory are used to define areas eligible for harvest and those that are not (protected areas, parks, etc.), or for specific insect outbreaks, the rules define the tree species (hosts) and age ranges of stands that are susceptible to insect disturbances. The model then uses these rules and applies mortality impacts to selected stands in the forest inventory. Disturbances are applied to individual stands, but the location of the stands is spatially referenced only to one of the 607 management units represented in the NFCMARS. Thus, while the emissions and subsequent removals associated with each stand can be tracked, the exact location of each stand is not known. Following disturbances, the model represents regeneration and forest growth based on user-specified rules about the type and rate of regeneration. In national-scale applications of the CBM-CFS3 in Canada, the default assumption is that a stand affected by a stand-replacing disturbance will regenerate to the same forest type (species and yield curve) previously growing on that site, unless land-use change results in a transition to a non-forested use. More information on the activity data currently used, the controls to simulate natural and anthropogenic disturbance impacts on spatially referenced stands, and the estimation of disturbance impacts are described in previous publications (e.g., Kurz et al. 2008a, 2008b, 2009; Stinson et al. 2011) and in Canada’s 2018 GHG inventory (Environment and Climate Change Canada 2018).

2.2. Separating natural disturbance and anthropogenic emissions and removals

The high interannual variation in natural disturbance emissions can mask trends resulting from human activities when forest GHG emissions and removals are reported using the MLP. We developed an alternative approach that separates the MLP emissions and removals into those from lands where carbon dynamics are dominated by natural disturbances and those from all remaining managed forest lands, where carbon dynamics are primarily influenced by human activities.

Inventory records in the CBM-CFS3 that define forest stands include information about the year and type of last disturbance, allowing the model to track the information needed to separate stands based on disturbance and management history. Where land-use changes occurred, the model records the year and the type of land-use change. This facilitates the reporting of GHG emissions and removals for IPCC land categories. This functionality was expanded to enable the partitioning of forest stands in Canada’s managed forest inventory into stands where carbon dynamics are dominated by natural disturbances and all other stands that are affected by human activities.

Stands considered to be dominated by natural disturbance effects are defined as (i) stands that have been affected by a stand-replacing wildfire or (ii) stands that have been partially disturbed (e.g., by insects or storms) causing aboveground biomass mortality exceeding 20% per year. Emission and subsequent removals in those stands are reported as natural disturbance fluxes until stands reach commercial maturity after stand-replacing wildfire or have regrown to their predisturbance biomass stocks after partial disturbances. The 20% mortality threshold for partial disturbances was selected because some natural disturbances (such as some defoliating insects and low severity bark beetles) cause only minor impacts on stand dynamics, even though they occur over large areas and are in many cases the causal agents contributing to stand density reductions that are part of forest dynamics. Emissions and removals from all remaining managed forest stands are reported in the component under anthropogenic influence. Figure 1 introduces a decision tree that summarizes the criteria for partitioning stands into the two components. At every annual time step, a stand can belong to only one component.

Changes from the natural disturbance component to the anthropogenic influence component are also triggered by salvage logging operations, which establish a legal obligation to demonstrate successful regeneration through natural regeneration, seeding, or planting. Collection of residential firewood may occur on lands affected by natural disturbances but has only a small impact on carbon stocks and does not contribute to regeneration outcomes. Therefore, collection of residential firewood does not trigger the transition from the natural disturbance to the anthropogenic reporting component. Emissions from the burning of residential...
Firewood are reported in the energy and harvested wood product sectors (Environment and Climate Change Canada 2018).

A common aspect of forest management in Canada is the requirement to develop both strategic (20+ year) and operational (1–5 year) management plans. The timing and location of planned harvesting and silvicultural activities are described in these plans. Economic and environmental considerations also influence the decision on which forest stands are scheduled for forest operations or silvicultural interventions. This planning process is central to forest management in Canada; it informed the approach used to separate forest stands that are predominantly under the influence of natural disturbances from those stands considered eligible for management activities.

In the initial implementation of the approach in Canada’s 2017 GHG inventory, the age of commercial maturity was fixed nationally at 60 years, representing a national average for when stands affected by natural disturbances are considered in forest management planning (Environment and Climate Change Canada 2017). Through consultations with forest management experts from Canadian provinces and territories, regionally differentiated age thresholds for the inclusion of forest stands in management plans were identified. The variable age thresholds were based on minimum harvest age, for broad species combinations, and stratified by ecozone across Canada (Table 1). The commercial maturity by species and region takes into account variable growth rates due to climate and species but also considers regional forest management objectives. Therefore, these variable age-based criteria represent how stands previously disturbed by large-scale natural disturbances are incorporated in operational forest management planning. All stands older than the age threshold are transitioned from the natural disturbance component to the anthropogenic component. These regionally differentiated age thresholds were first implemented in Canada’s 2018 GHG inventory.

While the goal of this new approach is to separate the emissions and removals into the two components, for the technical implementation of the approach and to better understand the contributions of different categories, we define eight stand categories and estimate the net fluxes for each. In Canada’s GHG inventory land category Forest Land, the eight categories are assigned to either the natural disturbance dominated or the anthropogenic influence components as follows:

1. forestry activities before 1990 (anthropogenic influence);
2. forestry activities after 1990 (anthropogenic influence);
3. low-intensity partial natural disturbances causing ≤20% aboveground biomass mortality after 1990 in stands already in the anthropogenic component (anthropogenic influence);
4. high-intensity partial natural disturbance causing >20% aboveground biomass mortality after 1990 and regrown to predisturbance biomass (anthropogenic influence);
5. high-intensity partial natural disturbance causing >20% aboveground mortality after 1990 and not yet regrown to predisturbance biomass (natural disturbance dominated);
6. stand-replacing natural disturbance (wildfire) before 1990 and older than the age of commercial maturity (anthropogenic influence);
7. stand-replacing natural disturbance (wildfire) before 1990 and younger than the age of commercial maturity (natural disturbance dominated); this also includes stands that have been affected by insects with ≤20% aboveground biomass mortality after 1990 that were already a part of this component;
8. stand-replacing natural disturbance (wildfire) after 1990 and younger than the age of commercial maturity (natural disturbance dominated); this also includes stands that have been affected by insects with ≤20% aboveground biomass mortality after 1990 that were already a part of this component.

Note that if low-intensity partial natural disturbances causing ≤20% aboveground biomass mortality after 1990 occurred in stands that were already in the natural disturbance dominated component, they remain reported in that component. An additional category “stands disturbed by wildfire after 1990 that have regrown to the age of commercial maturity” can exist but is not
considered here because such lands are not observed in the inventory time series (1990–2016).

The sum of net emissions and removals from categories 1, 2, 3, 4, and 6 is included in the component under anthropogenic influence and is reported for Canada’s managed forest in the national GHG inventory. The net flux from stands in the remaining categories (5, 7, and 8) is considered to be dominated by natural disturbances and is reported in the national GHG inventory but is not considered to be anthropogenic emissions and removals.

We implemented this approach to partition GHG fluxes from Canada’s managed forests into natural disturbance and anthropogenic components in Canada’s 2018 national GHG inventory. More information about the underlying data sources can be found in Chapter 6 and Annex 3.5 of the National Inventory Report (Environment and Climate Change Canada 2018).

3. Results

3.1. Area and net flux for each of the eight stand categories

Each of the eight categories contains forest stands that have carbon dynamics that are either dominated by natural disturbances or primarily under anthropogenic influence. The total stand area of each category (Figs. 2 and 3) and contribution to net fluxes (Fig. 3) change over time. The area of stands that have been disturbed since 1990 is increasing over time, while the area of stands affected by natural disturbances prior to 1990 is decreasing because some of these stands have regrown to the age of commer-

| Province or territory | Ecozone | Reconciliation unit | Age threshold (years) |
|-----------------------|---------|---------------------|-----------------------|
| Newfoundland          | Boreal Shield East | 1                   | 60                    |
| Labrador              | Taiga Shield East  | 3                   | 80                    |
| Labrador              | Boreal Shield East | 4                   | 67                    |
| Nova Scotia           | Atlantic Maritime | 5                   | 60                    |
| Prince Edward Island  | Atlantic Maritime | 6                   | 45                    |
| New Brunswick         | Atlantic Maritime | 7                   | 60                    |
| Quebec                | Atlantic Maritime | 11                  | 63                    |
| Quebec                | Mixedwood Plains  | 12                  | 73                    |
| Quebec                | Hudson Plains     | 13                  | 80                    |
| Quebec                | Taiga Shield East | 14                  | 80                    |
| Quebec                | Boreal Shield East| 15                  | 67                    |
| Ontario               | Boreal Shield West| 16                  | 67                    |
| Ontario               | Mixedwood Plains  | 17                  | 69                    |
| Ontario               | Hudson Plains     | 18                  | 80                    |
| Ontario               | Boreal Shield East| 19                  | 70                    |
| Manitoba              | Taiga Shield West | 21                  | 90                    |
| Manitoba              | Boreal Shield West| 22                  | 77                    |
| Manitoba              | Boreal Plains     | 23                  | 74                    |
| Manitoba              | Subhumid Prairies | 24                  | 65                    |
| Manitoba              | Hudson Plains     | 25                  | 80                    |
| Saskatchewan          | Taiga Shield West | 26                  | 90                    |
| Saskatchewan          | Boreal Shield West| 27                  | 80                    |
| Saskatchewan          | Boreal Plains     | 28                  | 76                    |
| Saskatchewan          | Subhumid Prairies | 29                  | 65                    |
| Saskatchewan          | Semiarid Prairies | 30                  | 65                    |
| Alberta               | Taiga Plains      | 31                  | 90                    |
| Alberta               | Taiga Shield West | 32                  | 90                    |
| Alberta               | Boreal Shield West| 33                  | 80                    |
| Alberta               | Boreal Plains     | 34                  | 87                    |
| Alberta               | Subhumid Prairies | 35                  | 65                    |
| Alberta               | Montane Cordillera| 36                  | 80                    |
| Alberta               | Semiarid Prairies | 37                  | 65                    |
| British Columbia      | Taiga Plains      | 38                  | 89                    |
| British Columbia      | Boreal Plains     | 39                  | 99                    |
| British Columbia      | Boreal Cordillera | 40                  | 89                    |
| British Columbia      | Pacific Maritime  | 41                  | 72                    |
| British Columbia      | Montane Cordillera| 42                  | 73                    |
| Yukon Territory       | Taiga Plains      | 44                  | 99                    |
| Yukon Territory       | Taiga Cordillera  | 45                  | 100                   |
| Yukon Territory       | Boreal Cordillera | 46                  | 77                    |
| Yukon Territory       | Pacific Maritime  | 47                  | 100                   |
| Northwest Territories | Taiga Plains      | 50                  | 90                    |
| Northwest Territories | Taiga Shield West | 51                  | 90                    |
| Northwest Territories | Boreal Plains     | 52                  | 87                    |
| Northwest Territories | Taiga Cordillera  | 53                  | 99                    |
| Northwest Territories | Boreal Cordillera | 54                  | 89                    |
| Nunavut               | Taiga Shield West | 58                  | 90                    |
| Nunavut               | Hudson Plains     | 59                  | 80                    |

Note: Corresponding maps can be found in the Supplementary Fig. S1 and at https://www.nrcan.gc.ca/forests/climate-change/carbon-accounting/13117.
cial maturity and transitioned into the anthropogenic influence component or are disturbed again and thereby transferred to one of the post-1990 disturbance categories. The area of stands affected by partial disturbances after 1990 that reach predisturbance biomass stocks is also slowly increasing over time. Overall, the total area of all stand categories with anthropogenic influence is approximately constant over time: the average for the 27-year period 1990 to 2016 is 172 million hectares (Mha), with a range of ±4%. The area of stands that are natural disturbance dominated is also fairly stable at 54 Mha, but because of the smaller base, the range expressed as percentage of the 27-year average is slightly larger (−6% to +5% of the 27-year average).

Stands with anthropogenic influence contribute an average estimated sink of −180 Mt CO₂e·year⁻¹ over the period 1990 to 2016 (not including emissions from harvested wood products) (Fig. 3A). The trend in the sink is correlated with the area affected by human activities, in particular harvest (as discussed below). The estimated net flux in stands dominated by natural disturbance fluctuated between a sink and a source with average emissions of 60 Mt CO₂e·year⁻¹ and large interannual variability for the 1990 to 2016 time series (Fig. 3G). Note that the sum of both components is equal to the net emissions and removals in managed forest lands. All reported flux estimates contain uncertainties that have been quantified (Metsaranta et al. 2017).

3.2. Summary of contributions for each stand category

3.2.1. Category 1: stands disturbed by forestry activities before 1990 (anthropogenic influence)

The area of stands affected by forestry activities (e.g., clearcutting), as well as afforestation before 1990, decreased from 83 to 54 Mha from 1990 to 2016, as some of the stands were affected by new harvest or natural disturbances (Fig. 3B). Despite the decreasing area, these stands contributed to an increasing sink of −82 to −179 Mt CO₂e·year⁻¹ from 1990 to 2001. This increase in removals was due to the increase in the average age of the stands as stands harvested in the years immediately prior to 1990 transitioned from net sources to net sinks; no new stands are added to this component after 1990.

3.2.2. Category 2: stands disturbed by forestry activities after 1990 (anthropogenic influence)

Stands affected by forestry activities after 1990 (e.g., clearcut or partial harvest) also include harvested areas affected by burning of forest residues and afforestation since 1990. The total area increased from zero at the start of 1990 to 29 Mha in 2016 (Fig. 3C). The area was a source throughout the period and estimated emissions peaked in 2005 at 163 Mt CO₂e·year⁻¹ and then declined to a source of 134 Mt CO₂e·year⁻¹ in 2016. The source decreased as the earliest harvested and afforested stands contributed a net sink to the overall GHG balance of these lands.

3.2.3. Category 3: stands affected by low-intensity partial natural disturbances after 1990 (anthropogenic influence)

Low-intensity partial insect disturbances that caused ≤20% mortality of aboveground biomass affected 14 Mha of stands after 1990 (Fig. 3D). Stands disturbed by insect infestations temporarily decreased aboveground biomass, but the impact was minor, and as a result, this stand category had estimated net removals ranging from −2 to −15 Mt CO₂e·year⁻¹ as the affected area increased.

3.2.4. Category 4: stands affected by high-intensity partial natural disturbances after 1990 that have reached predisturbance biomass stocks (anthropogenic influence)

The area of stands affected by partial natural disturbances with >20% mortality of aboveground biomass after 1990 and that have reached predisturbance biomass stocks was very small and increased from zero in 1990 to 4 Mha in 2016 (Fig. 3E).
Fig. 3. Net fluxes (left axis) and total stand area (right axis) of stand categories with anthropogenic (left column) and natural disturbance (right column) influences. In each column, the top graph represents the sum of the categories below. Data from Canada’s 2018 GHG inventory. Emissions associated with harvested wood products are not included. [Colour version online.]
Over this period, the estimated sink increased from zero to −7 Mt CO₂·year⁻¹.

3.2.5. Category 5: stands affected by high-intensity partial natural disturbances after 1990 that have not yet regrown to predisturbance aboveground biomass (natural disturbance dominated)

For stands affected by partial natural disturbances after 1990 with >20% mortality of aboveground biomass that have not reached predisturbance biomass stocks, the total area increases from zero at the start of 1990 to 11 Mha in 2016 (Fig. 3H). This category is a net source, particularly after 2000, with estimated emissions reaching 46 Mt CO₂·e·year⁻¹ in 2008 and declining thereafter.

3.2.6. Category 6: stands disturbed by wildfire before 1990 that have regrown to the age of commercial maturity (anthropogenic influence)

For stands disturbed by stand-replacing wildfires before 1990 that have regrown to the age of commercial maturity, the area decreases by 14 Mha from 1990 to 2016 (Fig. 3F). Over this period the estimated sink decreased from −153 to −102 Mt CO₂·e·year⁻¹ as the average age of the stands increases (no new stands are added to this component), and the area decreases as stands are again affected by natural disturbance or harvest.

3.2.7. Category 7: stands disturbed by wildfire before 1990 and have not yet regrown to the age of commercial maturity (natural disturbance dominated)

The area of stands that have not yet regrown to the age of commercial maturity after being disturbed by stand-replacing wildfires before 1990 decreases from 55 Mha in 1990 to 26 Mha in 2016 (Fig. 3J). The area is decreasing as stands reach the age threshold to re-enter the component under anthropogenic influence and because some stands are affected by new natural disturbances or harvesting. This stand category was an estimated net sink across the period from −64 to −82 Mt CO₂·e·year⁻¹ from 1990 to 2000, as stands re-grow, and then decreased to a net sink of −65 Mt CO₂·e·year⁻¹ in 2016 as the total stand area decreased.

3.2.8. Category 8: stands disturbed by wildfire after 1990 that have not yet regrown to the age of commercial maturity (natural disturbance dominated)

All stands disturbed by wildfire after 1990 have not yet regrown to the age of commercial maturity during the 1990 to 2016 time series of 27 years (Fig. 3I). The total area of stands in this category increases from zero at the start of 1990 to 19 Mha in 2016. This category includes the direct emissions from wildfires and was therefore a net source with high interannual variability. Due to variations in annual area burned, estimated emissions ranged from 20 Mt in 2002 to 270 Mt CO₂·e·year⁻¹ in 2015.

3.3. Relationship between forest management and reported GHG estimates

Very large natural disturbance driven emissions in managed forests were reported in previous editions of Canada’s national GHG inventory, which displayed no relationship between the reported estimates and anthropogenic activities (e.g., Environment and Climate Change Canada 2016). Using data from Canada’s 2018 national GHG inventory, we show that the reported anthropogenic GHG estimates in Canada’s managed forests would still be driven by natural disturbance impacts if the total net flux with the MLP approach was reported (Fig. 4A). The total net flux with the MLP approach and the natural disturbance component are highly correlated with areas burned but not with anthropogenic activities (Fig. 4B). The net flux of the anthropogenic component of managed forests correlates well with areas affected by forestry activities (Fig. 4C). This correlation is further improved when the anthropogenic component is combined with emissions from harvested wood products (HWP) originating from Canada’s forests, better representing the full forest sector contribution to anthropogenic emission and removals. The implementation of Canada’s refined estimation approach for managed forests results in trends in reported emissions and removals that are more closely correlated with forestry activities than they were when natural disturbance impacts were included in the reported estimates. The anthropogenic component (i.e., reported estimates) was a net sink for all years, with a large decrease in removals from −214 to −150 Mt CO₂·e·year⁻¹ from 1990 to 2007, followed by an increase to −163 Mt CO₂·e·year⁻¹ in 2009 and then remained relatively constant around −156 Mt CO₂·e·year⁻¹ to 2016. The net flux is more closely correlated with trends in the area disturbed by forestry activities, most notably, the increased harvest levels from 1990 to 2004 and then the drop in harvest levels to 2009 (Fig. 4C). However, the occurrence of natural disturbances still influenced the reported estimates as natural disturbances transferred stands out of the anthropogenic component, resulting in a reduction of carbon sinks.

Trends in the net GHG flux of stands varied across Canada (Fig. 5). For example, the net flux of stands with natural disturbance impacts fluctuated between a sink and a source in the eastern part of the Boreal Shield, an area with relatively few fires. Those stands contributed an average sink of 0.8 Mt CO₂·e·year⁻¹. In contrast, stands affected by natural disturbances in the Boreal Plains, an area with many fires, were predominantly a net source. Stands affected by natural disturbances in the Montane Cordillera were a sink from 1990 to 2001 and became a source due to large areas disturbed by severe insect outbreaks (Kurz et al. 2008a).

National totals in the anthropogenic component were dominated by trends in the Montane Cordillera and Boreal Plains ecozones (Figs. 5B and 5C). Wildfires and severe insect disturbances such as the mountain pine beetle in the Montane Cordillera and aspen defoliators in the Boreal Plains transferred stands to the natural disturbance component. This change in stand category resulted in a reduction in forest area and the associated lost sink in the anthropogenic influence component. In these two regions, increasing harvest rates, which includes salvage logging to recover wood killed by insects, also decreases removals because the decay of harvest residues leads to a net source in the early years after logging. The trend in some of the other regions such as the Boreal Shield was driven by changing harvest rates (Fig. 5A).

4. Discussion

4.1. Improved anthropogenic GHG estimates for Canada’s managed forests

Using a refined land-based approach reduces the large natural disturbance driven emissions variability reported in GHG estimates for Canada’s managed forests. Separating forest stands dominated by natural disturbance impacts from those primarily under anthropogenic influence also isolated the impacts associated with changes in regional harvest rates and showed that the trend in anthropogenic emissions and removals in the revised approach is correlated with regional trends in forest management activities in Canada’s managed forests. Regionally differentiated age thresholds for the transition of naturally disturbed stands to the anthropogenic component reflect regional differences in rates of recovery and management practices. While the approach tracks emissions and removals in the two components separately, it is important to note that the sum of both components is equivalent to estimates reported in previous GHG inventory editions. The new approach serves only to partition the fluxes into the two components. Refined attribution of changes in land-based GHG emissions and removals due to direct human activities aims to improve the reporting of anthropogenic GHG estimates and to enable tracking of the effects of forest management mitigation activities in national GHG inventory reports. The IPCC MLP assumption that all emissions and removals on managed lands are
Fig. 4. The net GHG flux from Canada’s managed forest, separated by anthropogenic and natural disturbance components with and without emissions from harvested wood products (HWP), plotted against area affected by natural disturbances (wildfires and insects) and forestry activities (e.g., clearcutting, partial cutting). Data from Canada’s 2018 National Inventory Report (Environment and Climate Change Canada 2018). [Colour version online.]
anthropogenic is a pragmatic approximation accepted due to a lack of alternative estimation methods (IPCC 2010). The approach developed and implemented for Canada demonstrates the large impact of natural disturbances on variability and trends in emission and removal estimates within the managed forest land and shows that the MLP is a poor proxy for anthropogenic emissions and removals and their trends in Canada’s managed forests. Partitioning the total MLP fluxes into a natural disturbance com-
ment and an anthropogenic component reduces the interannual variability of emissions and removals reported as the anthropogenic component under the MLP and increases their correlation with areas affected by forest management activities. Countries’ GHG estimates for the LU/LUCF sector may also include ecosystem responses to environmental change and natural effects (Houghton 2013; Grassi et al. 2018). There has been considerable interest in factoring out the impacts of direct human-induced changes in GHG emissions and removals on managed lands from those due to indirect human-induced environmental changes (carbon dioxide, fertilization, atmospheric nitrogen deposition, and climate change) and natural effects such as interannual variability due to weather and natural disturbances (Canadell et al. 2007; Kurz 2010; Houghton 2013). As the CBM-CFS3 is based on empirical growth and yield curves, simulation results do not include the impacts of indirect human-induced environmental changes that are not already captured in the empirical data. Consequently, it is not necessary to factor out the impacts of these indirect environmental effects in Canada’s managed forest estimates. However, stands affected annually by natural disturbances resulted in large interannual variation in previously reported GHG estimates due to wildfires and periodic insect outbreaks, and these masked subtler impacts of changes in forest management activities.

The attribution of land-based GHG emissions and removals to anthropogenic and natural effects is key in reconciling differences between countries’ GHG inventory reports and global carbon budget studies synthesized in IPCC assessment reports (McGuire et al. 2001; Erb et al. 2013; Houghton 2013; IPCC 2014; Grassi et al. 2017). Improved estimation of the anthropogenic GHG component of managed forests will also increase confidence in the ability to reflect the contribution of mitigation activities in the forest sector to meeting emission-reduction goals under the Paris Agreement. While the forest land base contribution to the global carbon cycle can only be assessed with the total forest emission and removal estimates, the relative contributions of anthropogenic activities and natural disturbances are better understood by their component fluxes.

The approach described in this paper is not free of uncertainty. We also examined an alternate approach in which stands transition to the anthropogenic influence component after the biomass or ecosystem carbon stocks prior to the stand-replacing wildfire had recovered to predisturbance levels, but this was not implemented because predisturbance ecosystem carbon stocks are not known for fires that occurred prior to 1990 and are likely to remain unknowable without resorting to a series of highly uncertain assumptions. In addition, the subdivision of lands into the two components contains a degree of uncertainty because the effect of past management activities on disturbance frequency and severity cannot always be clearly defined or attributed. For example, some stands primarily dominated by natural disturbance may in the past have been affected by fire suppression or insect control efforts, and therefore, a fraction of the natural disturbance emissions could arguably be attributed to past management actions. Another source of uncertainty is that the initial age in 1990 and the last disturbance type recorded or assumed can influence the initial subdivision of land into the two components and therefore subsequent trends. Further research will attempt to refine this initial subdivision of lands based on past disturbance types.

In addition, national GHG inventories do not quantify all land-based impacts on the atmosphere because they do not include the GHG fluxes from unmanaged lands. For example, in Canada, 121 Mha of forest in the north are classified as unmanaged for the purpose of GHG inventory reporting (Natural Resources Canada [NRCan] 2017; Ogle et al. 2018). The “Global Stocktake” planned under the Paris Agreement for 2023 will require estimates of all land-sector emissions and removals to determine progress towards meeting the goals of the Paris Agreement to keep temperature well below 2 °C. Thus, for the purposes of the Global Stocktake, emissions and removals from lands affected by natural disturbances and from unmanaged forests need to be quantified and combined with the estimates for managed lands. Quantification of emissions and removals in unmanaged lands is of particular importance because climate change impacts on forest GHG dynamics are potentially large in these unmanaged forests of Canada (Kurz et al. 2013).

4.2. Assessment against IPCC good practice and inventory reporting principles

The IPCC guidance states that while recognizing the complexity of the quantification of emissions and removals from forest management, inventory methods need to be practical and operational (IPCC 2006) and further noted that though inventories should estimate actual emissions in an inventory year, there is “a need to be able to identify the impact of mitigation and management efforts even where these are obscured by inter-annual variations in greenhouse gas fluxes for example by the impacts of natural processes (e.g., wildfire) or indirect human-induced processes (e.g., climate change impacts)” (IPCC 2010: 7).

Current inventory reporting guidelines for national GHG inventories encourage countries to refine anthropogenic emissions and removal estimates through higher tier methods, which can include improved methods to remove non-anthropogenic emissions and removals from reporting. The work carried out in this analysis conforms closely to the component separation approach described by the IPCC (2010) and is carried out in the spirit of continuing the work set out by the IPCC in their 2010 report. In the approach described here, anthropogenic and natural drivers of emissions and removals (components) are defined and separated according to apparent stand origin or influence. Anthropogenic drivers not only include harvest or other forest management interventions that have modified stand GHG balances, but also include all stands of natural origin that are eligible for harvest based solely on stand age and management practices. In contrast, all stands that undergo natural disturbance and are not of harvest age are reported in a separate category as they are under the direct influence of natural drivers.

The five guiding principles of inventory methodologies require that methods be judged according to their transparency, accuracy, completeness, comparability, and consistency. The transparency of Canada’s NFCMARS and the CBM-CFS3 is enhanced through peer-reviewed scientific publications describing the system, the core model, and its use (Kurz et al. 2009, Stinson et al. 2011, Smyth et al. 2014, and other publications). The methodological refinement presented here does not change the fundamental functioning of the model, only the way in which emissions are classified and summarized into two components with no impact on the totals.

The accuracy of the CBM has been compared with independently collected data (Shaw et al. 2014). In addition, uncertainty estimates for forest land in Canada’s national GHG inventory are calculated and reported annually using Monte Carlo approaches that consider uncertainties in model parameters, input data, and algorithms. This uncertainty assessment is described in detail in Metsaranta et al. (2017). We do not report uncertainty in this paper because the focus is on the new methods for separating stands into the different reported categories. However, uncertainty estimates are calculated and reported in the annual GHG inventory. In addition to the formal uncertainty analysis, other factors such as missing processes can contribute to uncertainties and these factors are identified and summarized elsewhere (Kurz et al. 2013).

Canada convened an international panel of forest scientists, who reviewed the initial implementation of the refined approach and provided recommendations for improvements. Initially, the age-based threshold used to transition stands from the natural disturbance component to the anthropogenic component was a...
national average of 60 years. The panel recommended that for stands affected by stand-replacing disturbances, the age at which stands re-enter the component with anthropogenic influence should be more representative of ecological variability in forests across Canada and therefore vary by region and possibly by stand type. This recommendation has been largely addressed by using regionally differentiated age-based criteria (Table 1) consistent with forest management principles defining eligibility of the stand for harvest.

Implementing regionally differentiated age thresholds, rather than a national average, resulted in a decrease in net removals throughout the time series as the age when stands are considered as recovered from natural disturbances was found to be greater than 60 years for almost all regions (Environment and Climate Change Canada 2018). Therefore, the choice of age thresholds will affect the allocation of emissions and removals to either the anthropogenic or the natural disturbance component. The establishment of age thresholds does, however, result in a relatively constant area of the anthropogenic component of the managed forest over time, suggesting that at the national scale, emissions and removals are not being influenced by changes in area for this component.

We also analyzed the relationship between the age thresholds and the average age of stands burned by wildfire. Over the period 1990 to 2016, for each stand in the inventory that was affected by wildfire, we compiled the age at the time of disturbance and the area burned. We then calculated the average age (area weighted by the area burned) of all stands that were burned between 1990 and 2016. We used the same area-burned estimates to also calculate the area-weighted average age threshold. The average age of the burned stands over the period 1990 to 2016 was 74.9 years, while the average age of the age threshold of the same burned areas was 84.3 years. Thus, on average, stands will transition from the natural disturbance to the anthropogenic component when they are 5.4 years older than when they were disturbed by wildfire. The five additional years of growth past the average age at which stands are typically disturbed by wildfire gives a degree of assurance that, on average, most stands will be reasonably close to the predisturbance condition when they meet the age thresholds for the transition to the anthropogenic component. Furthermore, the age-based threshold is the only pragmatic approach that can be implemented because, for disturbances that occurred prior to 1990, neither the stand age nor the emissions at the time of disturbance are known.

In terms of completeness, the CBM estimates and reports carbon stocks in all five pools defined by the IPCC, and in addition, research versions of the model address carbon pools that affect boreal carbon dynamics that are not included by the IPCC such as the moss pool (Bona et al. 2013, 2016). Comparability in forest estimates is inevitably a challenge due to differences in forest areas, ecological conditions, and forest management practices in different countries and therefore relies largely on the accuracy and consistency of the estimation methodology. As long as inventories are accurately portraying forest carbon pools and their evolution over time for their country-specific circumstance, forest emission and removal inventories can be considered comparable. For example, Pilli et al. (2016b) compared the reported GHG emissions from 26 EU countries using approaches based on national circumstances against a methodologically consistent approach. Lastly, consistency is achieved by applying consistent methods throughout the time series.

Further research is aimed at improving information on the last stand-replacing disturbance type and year. We are also working towards spatially explicit representation of forest dynamics, which will further increase the transparency of how emissions and removals in managed forest lands are partitioned into the natural disturbance dominated and anthropogenic influence components and how these components change over time.

5. Conclusions

The reporting of trends in human-induced GHG emissions and removals using the IPCC’s Managed Land Proxy, i.e., the assumption that all emissions and removals from managed lands result from human activities, can be confounded by the effects of natural disturbances. Here we describe and implement an approach that separates emissions and subsequent removals in stands subject to natural disturbances from all other emissions and removals in the managed forest. The resulting anthropogenic component of Canada’s managed forests was an estimated average sink of $-180$ Mt CO$_2$·y$^{-1}$ from 1990 to 2016, not including the emissions from harvested wood products. The trends were consistent with area harvested: removals decreased from $-214$ Mt CO$_2$·y$^{-1}$ in 1990 to $-150$ Mt CO$_2$·y$^{-1}$ in 2007, increased to $-163$ Mt CO$_2$·y$^{-1}$ in 2009, and fluctuated between $-150$ and $-160$ Mt CO$_2$·y$^{-1}$ thereafter. The natural disturbance component of Canada’s managed forests was an estimated average net source of $60$ Mt CO$_2$·y$^{-1}$ over the same period with high interannual variability, ranging from removals of $-48$ Mt to emissions of $235$ Mt CO$_2$·y$^{-1}$ due to annual area burned. This new approach removes the large variability in emissions caused by wildfires and reduces the trends associated with partial disturbances such as periodic large-scale insect outbreaks. The reported anthropogenic component of net emissions and removals from managed forests in Canada is much more closely correlated with trends in forest management activities compared with those reported using the IPCC Managed Land Proxy. This approach will be further refined to more accurately capture changes in emissions and removals associated with forest sector based climate change mitigation activities. Research is continuing to develop spatially explicit representation of forest dynamics that will increase reporting transparency by identifying stands whose carbon dynamics are primarily under the influence of forest management.

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