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Biomass status and dynamics over Canada's forests: Disentangling disturbed area from associated aboveground biomass consequences

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Abstract

Forested ecosystems dominated by trees, wetlands, and lakes occupy more than 65% of Canada's land base. This treed area is dynamic, subject to temporary reductions in area and biomass due to wildfire and timber harvesting, and increases due to successional processes and growth. As such, the net aboveground biomass accumulated over time is a function of multiple, complex factors: standing forests grow and accrue biomass over time, whereas disturbed forests lose biomass, and subsequent regeneration processes result in biomass accrual once again. Knowledge of these processes behind biomass gain and loss is important for a range of considerations including habitat provision, economic opportunities, and exchange of carbon between forests and the atmosphere. Herein, we used a 33 year satellite-derived time series of aboveground biomass estimates for Canada's forested ecosystems to quantify biomass dynamics partitioned by the presence or absence of disturbance, and by disturbance type. Findings suggest that over the analysis period considered (1984–2016), undisturbed forests accounted for accrual of 3.90 Petagrams (Pg) of biomass. In contrast, while occupying ~75% less area, disturbed forests accounted for a loss of 3.94 Pg biomass. Of this total biomass reduction, 45.4% can be attributed to wildfire, 43.8% to harvesting, 8.3% to non-stand replacing disturbances, and 2.5% to detectable roads and infrastructure development. Following disturbance, an additional 1.32 Pg of biomass were accrued during the analysis period, along with an additional 4.09 Pg in newly treed areas. Overall, Canada's forested ecosystems have realized a net increase in biomass of 5.38 Pg. Results of this analysis demonstrate the decoupling of area disturbed from the resulting biomass consequences by disturbance type, with large areas of wildfire accounting for a change in biomass that is similar to that of forest harvesting, which occurs over a much smaller area of mature and productive forest.

1. Introduction

Forests are a key element of the global carbon cycle. Forests, and forest management, play a key climate change mitigation role globally (Canadell and Raupach 2008). While forests provide a critical reservoir of terrestrial carbon, dynamic processes influence the size and stability of that reservoir. Regionally, soils, climate and other environmental factors as well as anthropogenic elements, influence the various functional and physical determinants of the forest components of the carbon cycle (Pan *et al* 2013). Changes in forest area and biomass as a function of forest management play an important role in the long-term carbon balance (Houghton 2005). Monitoring of forest biomass as a process rather than a state at a given point in time allows for insights related to disturbance history, regional productivity, and natural resource management. Forests of the boreal and temperate zones are unified in having high seasonal variability in temperatures and precipitation and a notable variety in history, management, and disturbance trends (Wulder *et al* 2007a, Brandt 2009). Forests in Canada are important repositories of carbon (Kurz *et al* 2013), with a realized balance related to factors such as wildfire, forest age, productivity, and climate (Price *et al* 2013). Canada's forests harbour biodiversity and provide habitats both within and outside protected areas (Andrew *et al* 2012). Canada's forests also support rural communities and economic activity through forestry activities, accounting for CA$24.6 billion to Canada's gross domestic product (GDP) in 2017 (Natural Resources Canada 2018). Forest dominated ecozones in Canada, represented by trees, wetlands, and lakes, occupy over 650 Mha (Wulder *et al* 2008) of which trees are found on 347 Mha (Natural Resources Canada 2018).

Large-area assessments of forest biomass have been enabled by the increased availability of remotely sensed data (Lu *et al* 2016). Indeed, mapping global aboveground biomass (AGB) is the primary driver of several current and planned Earth Observation satellite missions (Rodríguez-Veiga *et al* 2017, Duncanson *et al* 2019). In the absence of any direct physical linkage between AGB and reflected energy in spectral wavelengths, empirical assessments using passive optical data are often predicated on the estimation of forest structural parameters, which in turn are used in allometric equations to estimate biomass (Song 2013). The use of active remote sensing systems such as lidar or radar has likewise become increasingly common (Koch 2010, Zolkos *et al* 2013), as has the synergistic use of multiple data sources for AGB estimation (Sun *et al* 2011, Kaasalainen *et al* 2015, Urbazaev *et al* 2018).

AGB often forms the basis for estimating carbon, with biomass commonly divided by a factor of two to derive estimates of carbon, often without consideration of species or growth conditions (Smith *et al* 2004, Pilli *et al* 2013). While carbon pools in forest ecosystems include both above and belowground components, remote sensing informs primarily on the aboveground component (Lu *et al* 2006). Importantly, remote sensing can provide spatially-explicit estimates of AGB that represent both managed and unmanaged forests, and that can be generated at multiple time steps, addressing some of the key information needs of next-generation forest carbon models (Boisvenue and White 2019). Critically, these large-area, spatially-explicit time series of biomass estimates enable insights into aboveground forest biomass dynamics and the relative contribution of forest growth, disturbance, and regrowth over time (Powell *et al* 2010, Gómez *et al* 2014).

Following the opening of the United States Geological Survey Landsat archive in 2008 (Woodcock *et al* 2008, Wulder *et al* 2012a), there has been an availability of satellite data at management relevant scales (Landsat-4, -5, -7, and -8; 30 m pixels) from 1984 forward (Wulder *et al* 2019). From this satellite data resource, time series of spectral information can be assembled to provide information on change over time (Kennedy *et al* 2010, Huang *et al* 2010) including the labelling of change types (Kennedy *et al* 2015, Hermosilla *et al* 2015b). Importantly, the data from Landsat sensors are calibrated and allow for the generation of surface reflectance (Masek *et al* 2008). Radiometric correction to surface reflectance is required for time series analyses if models (for change detection, land cover classification, forest structure imputation, etcetera) are to be extrapolated in time or space (Song *et al* 2001). Top-of-Atmosphere (TOA) corrections are bulk corrections that are made to an entire image, rather than individual pixels, as is the case for surface reflectance corrections. TOA primarily adjusts for sun angle and earth-sun distance; however atmospheric effects can contaminate spectral indices in a manner that is non-linear (Myneni and Asrar 1994, Mcdonald *et al* 1998). The surface reflectance values generated from Landsat imagery can be combined with three-dimensional forest structure characterization from airborne laser scanning (lidar) to model AGB across large areas. Zald *et al* (2016) demonstrated an approach using a Random Forests implementation of Nearest Neighbor imputation to link collocated measures of forest structural attributes from lidar samples over Landsat derived surface reflectance values. Based upon this regional prototype, a national transect lidar survey (Wulder *et al* 2012b) was used to provide lidar-plots to calibrate and validate a boreal-wide set of models to estimate forest structure (Matasci *et al* 2018b). Following augmentation of this boreal lidar transect dataset with analogous data over the hemiboreal (focused on south and central British Columba), a national implementation was possible. Models were developed and extended over time and space using the relationships between the lidar-plot structural estimates and Landsat surface reflectance (Fekety *et al* 2015, 2018), thereby enabling estimation over the entirety of Canada's forested ecosystems and through time over a 33 year period (Matasci *et al* 2018a). These time series based estimates of forest structure provide a basis for investigation of biomass dynamics over Canada's forested ecozones.

Given current environmental and economic imperatives, a national baseline of aboveground forest biomass dynamics for Canada's forest dominated ecozones can inform science, policy, and reporting needs. With over three decades of satellite-derived forest structure information, including biomass (Matasci *et al* 2018a), combined with the location and timing of forest changes (Hermosilla *et al* 2015b), we now have the capacity to summarize AGB dynamics in a quantitative and spatially-explicit fashion. To demonstrate this capacity, our objective was to characterize Canada's aboveground forest biomass dynamics over three decades (1984–2016), accounting for biomass changes related to growth, disturbance, and post-disturbance regrowth,

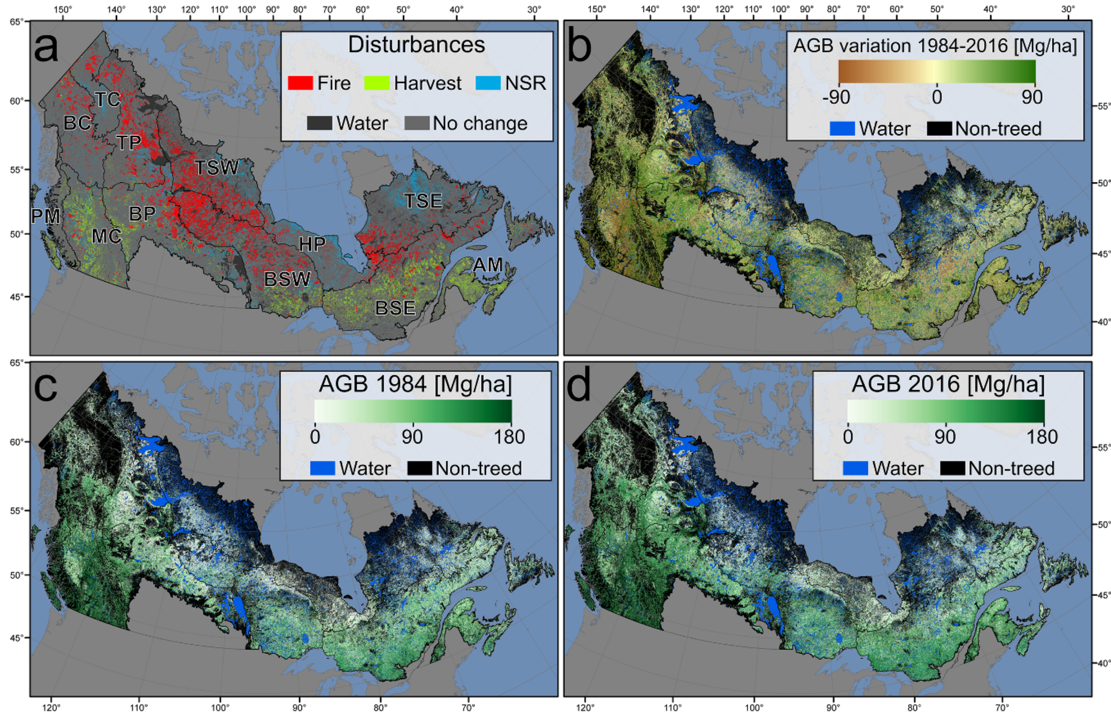

Figure 1. (a) Area disturbed by fire, harvest, and non-stand replacing (NSR) disturbances for the period 1985–2016. Note that changes related to roads and infrastructure are not included in this figure as they are not readily visible at this map scale. (b) Variation of aboveground biomass (AGB) between 1984 and 2016 (adapted from Matasci *et al* 2018a). (c) AGB in 1984. (d) AGB in 2016. Note that values above/below the upper/lower limits of the portrayed data ranges are truncated for cartographical representation. Canada's forested ecozones: Atlantic Maritime (AM), Boreal Cordillera (BC), Boreal Plains (BP), Boreal Shield East (BSE), Boreal Shield West (BSW), Hudson Plains (HP), Montane Cordillera (MC), Pacific Maritime (PM), Taiga Cordillera (TC), Taiga Plains (TP), Taiga Shield East (TSE), and Taiga Shield West (TSW).

partitioned by disturbance type (wildfire, harvest, non-stand replacing disturbances, roads and infrastructure), and regionally by forest ecozone.

2. Methods

2.1. Study area

The study area for this research is defined by the forest dominated ecozones of Canada following (Rowe 1972). Canada's forested dominated ecozones represent over 650 Mha and include boreal and hemiboreal ecosystems (Brandt 2009). These forest dominated ecosystems are occupied by trees, shrubs, water (lakes, rivers), and wetlands, among other categories of land cover (Wulder *et al* 2008). For reporting purposes, forest area is ascribed to locations that are presently treed or that in the absence of disturbance are typically treed (FAO 2018). Noting the distinctions between forest and treed area, in this research we refer to treed area as our biomass dynamics are focused on trees, not more generally on all forest area (which can temporally include, for instance following harvest or wildfire, herbs and shrubs).

Forest dominated ecosystems in Canada cover an extensive range of ecological and climatic conditions, presenting regional variability in prevailing tree species, stand structure, productivity, and growing conditions. Forest management is also variable across Canada's forested ecosystems; while northern latitudes are mostly unmanaged, forest management practices are common in southern areas, including harvest tenure agreements and fire suppression activities (Wulder *et al* 2004). Fire is the main stand replacing disturbance in Canada's forest dominated ecosystems (figure 1(a), table 1) and affects approximately 1.61 Mha annually, in contrast to the 0.64 Mha disturbed by harvest (White *et al* 2017). The impact of non-stand replacing disturbances which are subtle and/or gradual, longer-term events (e.g. pests, defoliation, water stress) impact an estimated 0.91 Mha on average each year with varying defoliation and mortality effects (Hermosilla *et al* 2019).

2.2. Data

The annual forest disturbance information on occurrence year and change type (figure 1(a)) were generated using the Composite2Change or C2C approach (Hermosilla *et al* 2016). The C2C approach considers the entirety of Landsat images in the USGS archive with surface reflectance values (calculated using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS; Masek *et al* 2006, Schmidt *et al* 2013)) to generate seamless, cloud free image composites from 1984 to 2017. First, best available pixel (BAP) composites were generated for each year by applying scoring functions that rank all observations

Table 1. Ecozone-level summary in hectares of treed area disturbed for the period 1985–2016, by disturbance agent.

Ecozone	Area	Treed area	Disturbed treed area			
			Fire	Harvest	Non-stand replacing disturbances	Road and infrastructure
Atlantic Maritime	20 436 453	15 834 141	42 238	3 035 254	484 062	132 262
Boreal Cordillera	44 469 737	22 542 829	2 294 921	183 239	902 276	48 082
Boreal Plains	71 318 202	42 383 647	4 796 842	2 444 650	1 573 808	332 683
Boreal Shield East	107 710 345	77 576 440	3 346 810	7 545 381	2 206 111	385 563
Boreal Shield West	81 817 371	54 036 365	11 789 628	2 126 370	2 267 830	73 036
Hudson Plains	36 408 956	18 591 531	1 404 856	44 154	1 168 932	12 442
Montane Cordillera	47 786 295	31 066 165	912 990	4 133 827	2 129 414	220 005
Pacific Maritime	20 129 744	11 366 866	50 000	1 139 050	292 099	92 770
Taiga Cordillera	25 124 723	5 241 016	603 960	50 819	269 505	10 912
Taiga Plains	61 991 369	31 102 385	5 150 282	221 092	702 370	42 121
Taiga Shield East	72 981 422	27 447 142	2 156 589	20 547	2 421 792	14 744
Taiga Shield West	59 806 905	17 307 682	6 435 898	14 139	634 943	1 487
Canada's forested ecosystems	649 981 522	354 496 209	38 985 014	20 958 521	15 053 142	1 366 107

to choose the optimum pixel for each location and year among all images acquired July 1st–August 31st, coinciding with the growing season for most of Canada's forested ecosystems (White *et al* 2014). The scoring functions assess the proximity of an acquisition to the target date (August 1st), presence and distance to clouds and cloud shadows (derived via Fmask algorithm; Zhu and Woodcock 2012), acquisition sensor (Landsat-7 ETM + following the scan line corrector failure is penalized), and atmospheric opacity for pre-Landsat-8 OLI acquisitions (Hermosilla *et al* 2019).

The resulting BAP composites are then refined using trend analyses of the time-series spectral values (Keogh *et al* 2001) to further remove noise from anomalous observations and fill data gaps applying temporal interpolation of the spectral values, resulting in seamless surface reflectance image composites (Hermosilla *et al* 2015a). The spectral trend analysis enabled the detection of changes and the characterization of temporal dynamics of disturbances between 1985 and 2016 (i.e. no change events are detected the first and last years of the time series: 1984, 2017). Then, for these 32 years, change events were attributed to a disturbance agent class, applying an object-based analysis on the spectral, temporal and geometrical characteristics of disturbances using a Random Forest classifier (Hermosilla *et al* 2015b). Disturbance agent classes include fire, harvest, road/infrastructure, and non-stand replacing disturbances. Non-stand replacing disturbances represent persistent, gradual changes in the vegetation's spectral response, which often do not involve a change in the land cover class (e.g. insects, water stress, disease). Canada-wide annual land cover maps were generated using the virtual land cover engine (VLCE) framework (Hermosilla *et al* 2018). This framework utilizes the C2C seamless surface reflectance image composites, together with C2C forest disturbance information, knowledge of vegetation succession, and logical rules to produce time-consistent annual land cover products with reduced instances of spurious classification results. The land cover map legend is composed of 12 classes, of which four represent treed vegetation, including wetland-treed, coniferous, broadleaf, and mixedwood.

Wall to wall, 30 m pixel, annual, aboveground, currently treed biomass maps from 1984 (figure 1(c)) to 2016 (figure 1(d)) were obtained from the Landsat-derived structural layers generated in Matasci *et al* (2018a) by temporally extending the methodology introduced in Matasci *et al* (2018b). These layers included lidar-metrics (elevation (i.e. canopy height, above ground level) mean, elevation standard deviation, elevation coefficient of variation, elevation 95th percentile, canopy cover, and canopy cover above mean height) and inventory attributes (Lorey's height, basal area, stem volume, and total biomass). The forest structure maps were produced using an imputation approach that combined lidar-derived forest structure metrics and the seamless surface reflectance image composites. Landsat spectral information and topographic ancillary data were used as predictor variables, and as detailed in Matasci *et al* (2018b) structural forest attributes were estimated annually for all pixels identified as treed by the annual VLCE land cover maps.

2.3. Analysis

We analyzed the AGB dynamics in Canada's forested ecosystems using satellite-derived time series of biomass maps for the period 1984–2016. To better capture and understand the role of the different components of forest biomass dynamics, we defined three partitions within which to consider AGB dynamics: (i) undisturbed persistent forest (AGB gain), (ii) disturbed forest (AGB gain and loss), and (iii) newly treed areas (AGB gain). Newly treed areas can either be where treed areas have expanded previously untreed areas, afforested areas, or most commonly

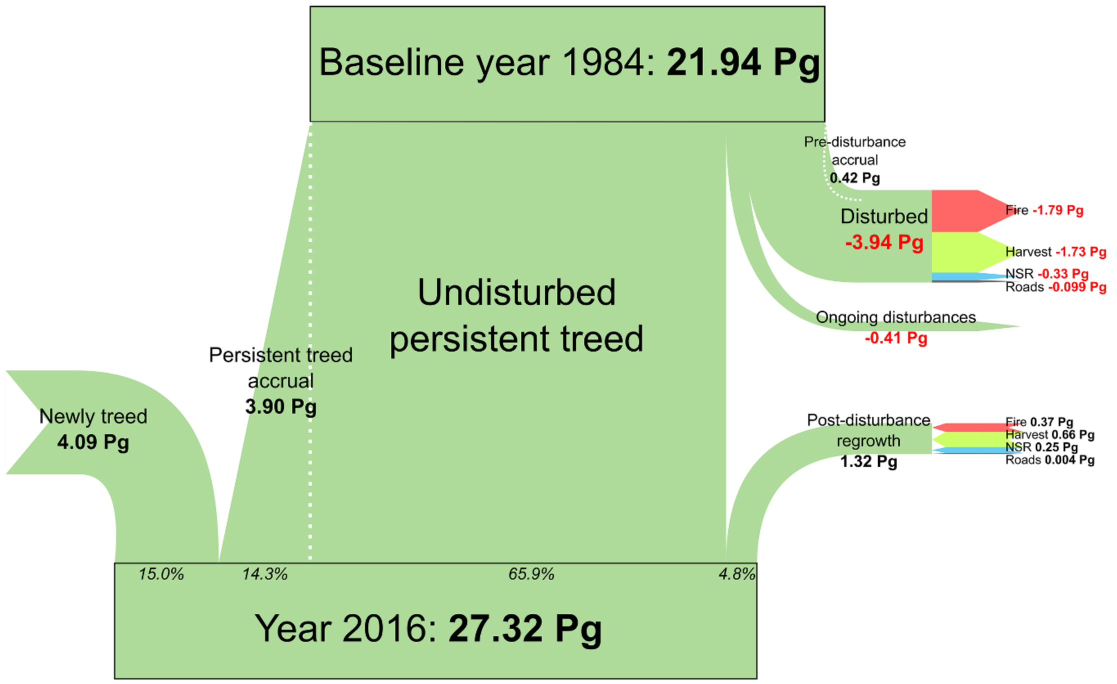

Figure 2. Summary of aboveground biomass (AGB) balance and dynamics in Canada's forested ecosystems between 1984 and 2016.

areas that were disturbed prior to the study baseline year (1984). We stratified our analysis, reporting our results by disturbance type and forested ecozone. To characterize biomass dynamics, we calculated the mean, standard deviation, minimum, and maximum annual AGB (in Pg), as well as the annual AGB density (in $\mathrm{Mg \cdot yr^{-1} \cdot ha^{-1}}$), for the treed area within Canada's forest ecosystems, and by ecozone. We also reported total AGB accrual or loss (in Pg), the annual rate of AGB accrual or loss (in $\mathrm{Tg \cdot yr^{-1}}$), as well as the annual rate of AGB density accrual or loss (in $\mathrm{Mg \cdot yr^{-1} \cdot ha^{-1}}$).

Undisturbed persistent forest includes those areas that were persistently occupied by treed vegetation with no disturbances detected during the analysis period. These standing forest areas are dominated by vegetation growth and biomass accrual over time. Disturbed forest represent those treed areas that experienced disturbances over the analysis period, attributed to four disturbance agents: fire, harvest, non-stand replacing disturbances, and roads and infrastructure. Disturbed forests were comprised of three main temporal components: vegetation growth and AGB accrual prior to the disturbance event, biomass loss resulting from the disturbance, and AGB gain resulting from post-disturbance regeneration and regrowth processes. Within disturbed forests we also identify and report on AGB loss due to long-term disturbance processes that were ongoing at the end of the analysis period (e.g. drought stress, defoliation). Newly treed forest areas are those that did not have treed vegetation at the beginning of the analysis period (1984), but that were treed at the end of this period (2016).

3. Results

3.1. Overall biomass balance and dynamics over Canada's forests

A summary of the overall aboveground treed biomass balance and dynamics in Canada's forested ecosystems for the analysis period 1984–2016 is shown in figure 2. In 1984, Canada's forest area (table 1) comprised 21.94 Pg of AGB. By the end of the analysis period in 2016, the treed AGB was 27.32 Pg, resulting in a net overall increase in AGB of 5.38 Pg. Undisturbed forests accounted for an accrual of 3.90 Pg of AGB. Disturbed forest areas had an AGB loss of 3.94 Pg, with a subsequent post-disturbance AGB gain in these areas of 1.32 Pg, which resulted in a net AGB balance of −2.62 Pg in disturbed treed areas. Of note, pre-disturbance AGB accrual in these disturbed areas, accounted for 0.42 Pg. Disturbance events that were ongoing at the end of the analysis period (2016) represented an AGB loss of 0.41 Pg. Finally, AGB accrual due to an increase in the area of treed vegetation was 4.09 Pg.

Table 2 summarizes overall AGB dynamics for 1984–2016 by forested ecozone. The ecozones with the largest average annual estimate of AGB are the Boreal Shield East (5.453 Pg) and Montane Cordillera (3.983 Pg), while the Taiga Cordillera (0.172 Pg) and Taiga Shield West (0.452 Pg) had the smallest average annual estimate of AGB. Relative to

Table 2. Summary of aboveground biomass (AGB) status and dynamics for the period 1984–2016, by forested ecozone and for Canada's forested ecosystems. AGB density values computed using the treed area for each ecozone, as reported in table 1.

Ecozone	Mean of total annual AGB (Pg)	Standard deviation of total annual AGB (Pg)	Minimum of total annual AGB (Pg) (year)	Maximum of total annual AGB (Pg) (year)	Mean of total annual AGB density ($Mg \cdot ha^{-1}$)
Atlantic Maritime	1.282	0.073	1.169 (1984)	1.402 (2015)	80.99
Boreal Cordillera	1.404	0.119	1.165 (1984)	1.604 (2016)	62.28
Boreal Plains	3.324	0.409	2.675 (1984)	4.032 (2016)	78.42
Boreal Shield East	5.453	0.231	5.076 (1984)	5.903 (2016)	70.29
Boreal Shield West	3.019	0.225	2.700 (1984)	3.500 (2016)	55.87
Hudson Plains	0.567	0.076	0.474 (1984)	0.744 (2016)	30.51
Montane Cordillera	3.983	0.065	3.851 (2007)	4.050 (1999)	128.21
Pacific Maritime	2.077	0.114	1.888 (1984)	2.258 (2016)	182.69
Taiga Cordillera	0.172	0.025	0.125 (1984)	0.222 (2016)	32.87
Taiga Plains	1.637	0.195	1.347 (1984)	2.030 (2016)	52.62
Taiga Shield East	0.913	0.086	0.803 (1984)	1.127 (2016)	33.28
Taiga Shield West	0.452	0.026	0.421 (1998)	0.497 (1988)	26.10
Canada's forested ecosystems	24.283	1.499	21.942 (1984)	27.325 (2016)	68.50

Table 3. Summary of aboveground biomass (AGB) dynamics over undisturbed persistent forests for the period 1984–2016, by forested ecozone and for Canada's forested ecosystems. AGB density values were computed using the treed area for each ecozone, as reported in table 1.

Ecozone	Undisturbed persistent treed area (Mha)	Total AGB accrual (Pg)	Annual AGB accrual rate ($Tg \cdot yr^{-1}$)	Annual AGB density accrual ($Mg \cdot ha^{-1} \cdot yr^{-1}$)
Atlantic Maritime	8.98	0.105	3.266	0.36
Boreal Cordillera	14.25	0.176	5.494	0.39
Boreal Plains	25.60	0.945	29.544	1.15
Boreal Shield East	53.56	0.701	21.916	0.41
Boreal Shield West	30.70	0.685	21.400	0.70
Hudson Plains	11.81	0.171	5.333	0.45
Montane Cordillera	20.68	0.158	4.945	0.24
Pacific Maritime	8.51	0.230	7.176	0.84
Taiga Cordillera	2.48	0.026	0.812	0.33
Taiga Plains	18.45	0.482	15.060	0.82
Taiga Shield East	17.76	0.165	5.142	0.29
Taiga Shield West	7.06	0.060	1.881	0.27
Canada's forested ecosystems	219.84	3.903	121.969	0.55

the area of the ecozone covered by treed vegetation, the largest average annual AGB densities were found in the hemi-boreal ecozones of the Pacific Maritime (182.69 $Mg \cdot ha^{-1}$) and Montane Cordillera (128.21 $Mg \cdot ha^{-1}$) ecozones. Conversely, the lowest average annual biomass densities were found in the northernmost forested ecozones of the Taiga Shield West (26.10 $Mg \cdot ha^{-1}$) and Hudson Plains (30.51 $Mg \cdot ha^{-1}$).

3.2. Biomass dynamics in undisturbed persistent forest

Between 1984 and 2016, Canada's undisturbed forest encompassed 219.8 Mha and had a net total AGB accrual of 3.90 Pg (figure 2). The Boreal Plains (0.945 Pg), Boreal Shield East (0.701 Pg), and Boreal Shield West (0.685 Pg) ecozones had the largest accrual of AGB and the greatest annual AGB accrual rates (table 3). By area unit, the highest annual AGB density accrual rates were found in the Boreal Plains (1.15 $Mg\ ha^{-1}\ yr^{-1}$), Pacific Maritime (0.84 $Mg\ ha^{-1}\ yr^{-1}$), and Taiga Plains (0.82 $Mg\ ha^{-1}\ yr^{-1}$), whereas Montane Cordillera (0.24 $Mg\ ha^{-1}\ yr^{-1}$) and Taiga Shield West (0.27 $Mg\ ha^{-1}\ yr^{-1}$) presented the lowest values. Total AGB accrual in undisturbed forest for the analysis period also varied by latitude (figure 3). The maximum area of undisturbed forest was located in the latitudes 51°–52° and 52°–53°, with an area of 36.7 Mha and 33.9 Mha respectively; however, the greatest biomass accruals were found at 49°–50° (0.32 Pg) and at 55°–56° (0.31 Pg).

3.3. Biomass dynamics in disturbed areas

A total of 76.36 Mha of treed vegetation were disturbed in Canada's forested ecosystems during 1985–2016, resulting in a loss of 3.94 Pg of AGB (table 4). The highest annual AGB density loss rates were found in the Pacific Maritime ecozone ($-4.80\ Mg\ yr^{-1}\ ha^{-1}$). The Pacific Maritime ecozone is one of the most productive forest ecozones in Canada (White *et al* 2017) with the highest biomass

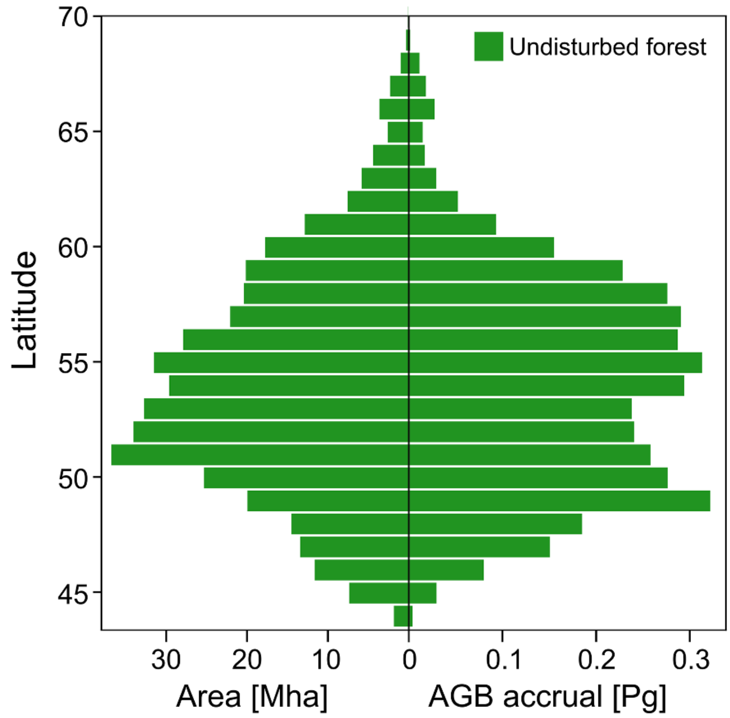

Figure 3. Latitudinal distribution of undisturbed treed area and total aboveground biomass (AGB) accrual between 1984 and 2016.

density of all forested ecozones (table 2), and with forest harvesting as the dominant disturbance agent (table 1). The lowest annual AGB loss rates per area unit were found in the Taiga Shield East ecozone (-0.58 Mg yr^{-1} ha^{-1}).

From the 76.4 Mha treed-vegetation disturbed in Canada's forested ecosystems during 1985–2016, 39 Mha were affected by wildfires, 21 Mha by harvesting, 15.1 Mha by non-stand replacing disturbances, and 1.4 Mha by road and infrastructure construction (table 1). Thus, although the area impacted by wildfire was almost twice the area impacted by harvesting, these two disturbance types accounted for similar amounts of total AGB loss (-1.790 Pg for wildfire and -1.726 Pg for harvest; table 5). Conversely, non-stand replacing disturbances resulted in an AGB loss of 0.325 Pg, and the construction of roads and infrastructure resulted in a total AGB loss of 0.099 Pg (table 5).

These overall trends are echoed in the annual data, whereby the area impacted by a particularly disturbance type is not commensurate with the loss of AGB (figure 4). For example, the AGB impacts of harvesting are five times that of non-stand replacing disturbances, although harvesting impacts only 1.3 times more area than non-stand replacing disturbances. Overall, there is relative consistency in the annual values of area disturbed and AGB loss; however the years with the greatest AGB losses (i.e. 1989, 1995, 2015; table 1) corresponded with years of exceptional fire activity (Coops *et al* 2018). The latitudinal distribution of total disturbed area and AGB loss (1985–2016), categorized by disturbance agent, highlights differences in the geographic distribution of disturbance events across Canada's forested ecosystems (figure 5). Harvesting and the construction of roads and infrastructure are common at the southern extent of Canada's forests, whereas wildfires are prominent at northernmost latitudes, and non-stand replacing disturbances are widespread. The greatest AGB losses occurred at the latitudes 50°–51° (0.40 Pg) and 49°–50° (0.32 Pg), coinciding with areas where forest harvesting was more prevalent (5.2 Mha and 5.0 Mha respectively).

The regrowth of treed vegetation following disturbance events resulted in a gain of 1.317 Pg of AGB in Canada's forested ecosystems, at an annual rate of 42.5 Tg yr^{-1} or 0.56 Mg yr^{-1} ha^{-1} (table 4). Higher annual rates of AGB accrual per area unit were found in the Pacific Maritime (2.17 Mg yr^{-1} ha^{-1}) and Montane Cordillera (1.15 Mg yr^{-1} ha^{-1}). In contrast, the Taiga Shield West (0.13 Mg yr^{-1} ha^{-1}) and Taiga Shield East (0.22 Mg yr^{-1} ha^{-1}) ecozones had the lowest rate of post-disturbance AGB accrual per area unit. By disturbance type, approximately half of the total AGB accrual resulted from harvested areas (0.656 Pg), followed by fire (0.369 Pg), non-stand replacing disturbances (0.254 Pg), and road and infrastructure (0.038 Pg) (table 6). The annual rate of AGB density gain following harvesting (1.01 Mg yr^{-1} ha^{-1}) is approximately triple that of AGB density gain following wildfires (0.31 Mg yr^{-1} ha^{-1}), which is likely a result of harvesting occurring in more productive

Table 4. Summary of aboveground biomass (AGB) dynamics over disturbed areas, post-disturbance regrowth, and ongoing disturbances for the period 1985–2016, by forested ecozone and for the entirety of Canada's forested ecosystems. Annual values for AGB loss computation in disturbed areas involved 32 years. Annual values for AGB accrual computation in post-disturbance regrowth areas involved 31 years.

	Disturbed areas				Post-disturbance regrowth			Ongoing disturbances	
Ecozone	Area disturbed (Mha)	Total ABG loss (Pg)	Annual rate of AGB loss ($Tg \cdot yr^{-1}$)	Annual rate of AGB density loss ($Mg \cdot yr^{-1} \cdot ha^{-1}$)	Total ABG (Pg)	Annual rate of AGB accrual ($Tg \cdot yr^{-1}$)	Annual rate of AGB density accrual ($Mg \cdot yr^{-1} \cdot ha^{-1}$)	Area (Mha)	Total AGB loss (Pg)
Atlantic Maritime	3.69	−0.175	−5.457	−1.48	0.115	3.715	1.01	0.25	−0.019
Boreal Cordillera	3.43	−0.147	−4.584	−1.34	0.032	1.042	0.30	0.44	−0.023
Boreal Plains	9.15	−0.553	−17.269	−1.89	0.196	6.309	0.69	0.86	−0.064
Boreal Shield East	13.48	−0.630	−19.675	−1.46	0.220	7.093	0.53	1.28	−0.069
Boreal Shield West	16.26	−0.643	−20.096	−1.24	0.190	6.137	0.38	0.88	−0.045
Hudson Plains	2.63	−0.080	−2.486	−0.94	0.042	1.352	0.51	0.25	−0.005
Montane Cordillera	7.40	−0.785	−24.527	−3.32	0.265	8.539	1.15	0.87	−0.102
Pacific Maritime	1.57	−0.242	−7.553	−4.80	0.106	3.413	2.17	0.12	−0.017
Taiga Cordillera	0.94	−0.026	−0.813	−0.87	0.007	0.231	0.25	0.15	−0.005
Taiga Plains	6.12	−0.333	−10.394	−1.70	0.085	2.730	0.45	0.97	−0.027
Taiga Shield East	4.61	−0.085	−2.655	−0.58	0.032	1.017	0.22	0.83	−0.021
Taiga Shield West	7.09	−0.244	−7.622	−1.08	0.029	0.920	0.13	0.45	−0.013
Canada's forested ecosystems	76.36	−3.940	−123.131	−1.61	1.317	42.499	0.56	7.36	−0.409

Table 5. Summary of aboveground biomass (AGB) loss for the period 1985–2016, by disturbance type and forested ecozone and for the entirety of Canada's forested ecosystems.

Ecozone	Fire			Harvest			Non-stand replacing			Roads and infrastructure		
	Total AGB loss (Pg)	Annual rate of AGB loss ($Tg\,yr^{-1}$)	Annual rate of AGB density loss ($Mg\,yr^{-1}\,ha^{-1}$)	Total AGB loss (Pg)	Annual rate of AGB loss ($Tg\,yr^{-1}$)	Annual rate of AGB density loss ($Mg\,yr^{-1}\,ha^{-1}$)	Total AGB loss (Pg)	Annual rate of AGB loss ($Tg\,yr^{-1}$)	Annual rate of AGB density loss ($Mg\,yr^{-1}\,ha^{-1}$)	Total AGB loss (Pg)	Annual rate of AGB density loss ($Mg\,yr^{-1}\,ha^{-1}$)	Annual rate of AGB density loss ($Mg\,yr^{-1}\,ha^{-1}$)
Atlantic Maritime	−0.002	−0.068	−1.60	−0.151	−4.724	−1.56	−0.015	−0.462	−0.95	−0.006	−0.203	−1.54
Boreal Cordillera	−0.118	−3.690	−1.61	−0.010	−0.327	−1.78	−0.015	−0.482	−0.53	−0.003	−0.085	−1.78
Boreal Plains	−0.267	−8.335	−1.74	−0.231	−7.221	−2.95	−0.032	−1.015	−0.65	−0.022	−0.698	−2.10
Boreal Shield East	−0.153	−4.795	−1.43	−0.423	−13.223	−1.75	−0.035	−1.083	−0.49	−0.018	−0.574	−1.49
Boreal Shield West	−0.469	−14.648	−1.24	−0.143	−4.468	−2.10	−0.028	−0.872	−0.38	−0.003	−0.108	−1.48
Hudson Plains	−0.060	−1.885	−1.34	−0.002	−0.065	−1.47	−0.017	−0.524	−0.45	0.0004	−0.012	−0.95
Montane Cordillera	−0.094	−2.950	−3.23	−0.531	−16.600	−4.02	−0.131	−4.099	−1.92	−0.028	−0.877	−3.99
Pacific Maritime	−0.007	−0.234	−4.67	−0.208	−6.506	−5.71	−0.013	−0.391	−1.34	−0.014	−0.423	−4.56
Taiga Cordillera	−0.021	−0.666	−1.10	−0.002	−0.048	−0.95	−0.003	−0.087	−0.32	0.0003	−0.011	−0.98
Taiga Plains	−0.288	−8.994	−1.75	−0.023	−0.728	−3.29	−0.018	−0.572	−0.81	−0.003	−0.100	−2.38
Taiga Shield East	−0.076	−2.378	−1.10	−0.0005	−0.014	−0.69	−0.008	−0.254	−0.10	−0.0003	−0.009	−0.62
Taiga Shield West	−0.233	−7.286	−1.13	−0.001	−0.016	−1.14	−0.010	−0.318	−0.50	−0.0001	−0.001	−0.96
Canada's forested ecosystems	−1.790	−55.928	−1.43	−1.726	−53.941	−2.57	−0.325	−10.160	−0.67	−0.099	−3.102	−2.27

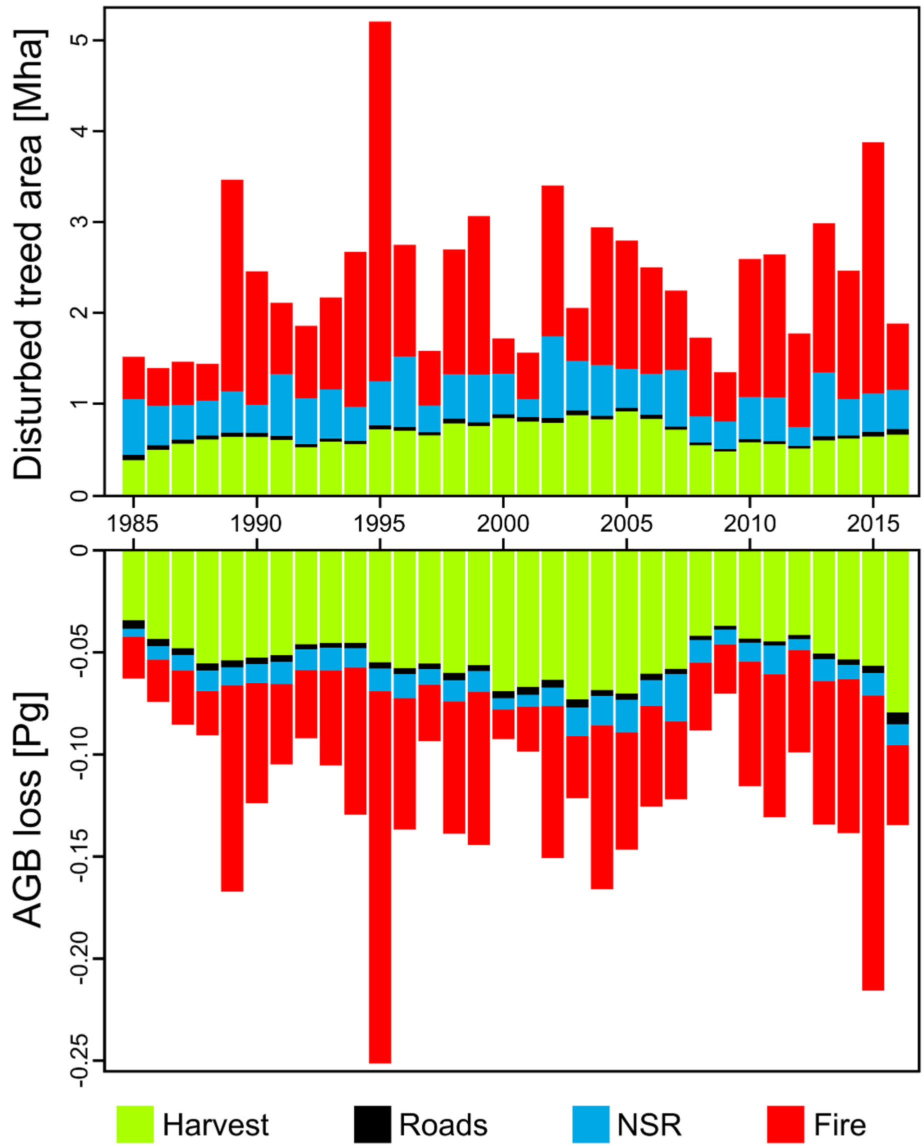

Figure 4. Total annual area impacted by different disturbance types (harvest, roads and infrastructure [Roads], non-stand replacing [NSR], fire), and corresponding losses in aboveground biomass (AGB), for the entirety of Canada's forested ecosystems.

environments and policies that mandate regeneration following harvesting (Haddon 1997, White *et al* 2017, Hermosilla *et al* 2019).

The disturbance events that were still ongoing at the end of the analysis period (2016) affected 7.36 Mha nationally, resulting in a total loss of 0.409 Pg of AGB (see table 4). The largest AGB losses due to ongoing disturbances were found in the Montane Cordillera (−0.102 Pg) and Boreal Shield East (−0.069 Pg) ecozones. In contrast, the Hudson Plains (−0.005 Pg) and Taiga Cordillera (−0.005 Pg) had the lowest AGB loss attributable to ongoing disturbances.

3.4. Biomass dynamics in newly treed areas

During the analysis period (1984–2016) across Canada's forested ecosystems a total of 61.05 Mha became treed in relation to the baseline year (1984) (see table 7). These areas are predominantly composed of recovering forests that were disturbed prior to the analysis period, but also by areas with afforestation and expansion of treed vegetation. The areas occupied by newly treed vegetation involved a total AGB gain of 4.09 Pg during the analysis period. In absolute terms, the largest ecozones (Boreal Shield East and Boreal Shield West) had the largest gain in treed area. The Boreal Plains (21.219 Tg yr^{-1}) and Boreal Shield East (19.018 Tg yr^{-1}) had the greatest annual rate of AGB accrual.

4. Discussion

Using a single, consistent national data source, we have quantified more than three decades of total treed AGB dynamics in Canada's forested ecosystems as a function of different disturbance types. We partitioned and independently analyzed the annual gain (or loss) of treed AGB for undisturbed persistent

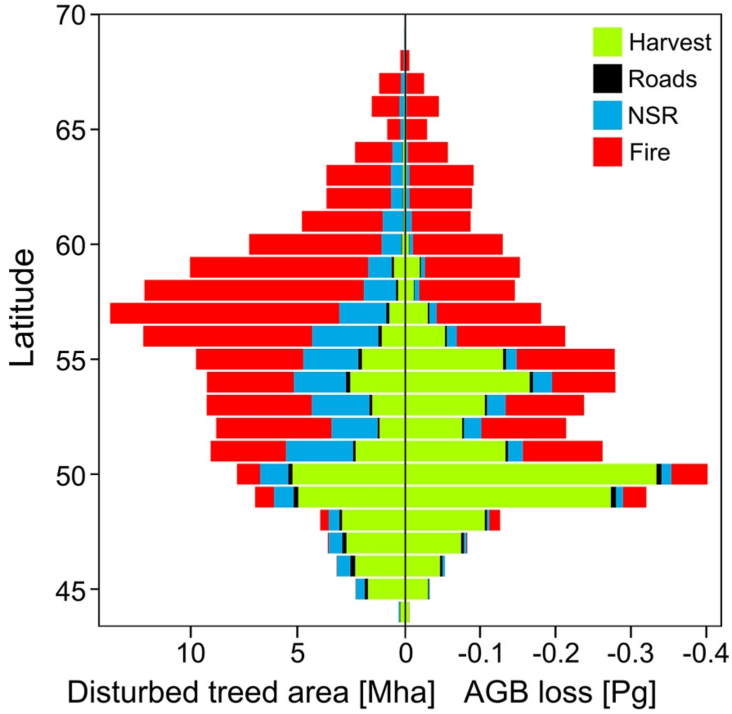

Figure 5. Total area impacted by different disturbance types (harvest, roads and infrastructure [Roads], non-stand replacing [NSR], fire) and total aboveground biomass (AGB) loss, by latitude for the entirety of Canada's forested ecosystems.

forest, disturbed forest, and newly treed areas. Herein, we quantified the relative contributions of each of these partitions to the AGB dynamics of Canada's forested ecosystems, highlighting the incremental nature of forest growth over broad areas, and comparing that to the punctual, larger magnitude changes in AGB that are typically associated with stand replacing disturbances (Wulder *et al* 2007b). The role of growth of undisturbed forests in accruing biomass was evident; the gradual addition of biomass from large areas of standing forest resulted in an AGB gain of 3.90 Pg, which is similar to the total amount of AGB lost to disturbance over the same time period (−3.94 Pg). Our results indicate that overall, Canada's forested ecosystems have realized a net increase in biomass of 5.38 Pg during the period 1984–2016, for a total AGB of approximately 27.32 Pg in 2016.

During the analysis period considered, most of Canada's forested ecozones had positive annual balances of AGB, with their minimum and maximum average total annual AGB values occurring at the beginning and end of the analysis period, respectively (table 2). Exceptions to this included the Montane Cordillera and Taiga Shield West ecozones. The Montane Cordillera experienced a spatially extensive epidemic infestation of mountain pine beetle during the analysis period, with the maximum total annual AGB in 1999 corresponding to the beginning of the outbreak in the late 1990s, and the minimum total annual AGB in 2007, corresponding approximately to the peak of the outbreak in around 2005 (Kurz *et al* 2008a). The Taiga Shield West is one of the most fire-disturbed ecozones in Canada, with approximately 0.65% of the ecozone are disturbed by fire annually, greatly exceeding the national average of 0.3% (White *et al* 2017).

In order to contextualize our findings, we examined AGB estimates for Canada's forests reported in other studies; noting that there are differences in the area analyzed, the data and technologies used (e.g. field plots, forest inventory data, remote sensing), the biomass components reported, and whether the estimates are measured or modelled, all of which can preclude a direct comparison to the numbers we derived from the approach reported herein (Duncanson *et al* 2019). In a synthesis of carbon in Canada's boreal forest, Kurz *et al* (2013) reported that the managed portion of Canada's boreal forest (representing 54% of total boreal forest area) contained 14.3 Pg of carbon or approximately 28 Pg biomass in aboveground biomass, dead organic matter, and soil pools. Wood and Layzell (2003) report a biomass carbon stock of ~15 800 Mt C, or 28.6 Pg of biomass for the timber productive forest in Canada. The NFI estimated that Canada had 29.6 billion short tonnes (26.85 Pg) of biomass, with 27.3 billion short tonnes (24.76 Pg) on forest land (Power and Gillis, 2006). Considering the independence of the approaches followed in the aforementioned studies, using disparate data and methods, the general agreement of the total biomass values, with the 27.32 Pg reported herein, is notable.

Table 6. Summary of aboveground biomass (AGB) dynamics following post-disturbance regrowth for the period 1985–2016, by disturbance type and forested ecozone and for the entirety of Canada's forested ecosystems. Note that decimal places are adjusted as required to show significant figures.

	Wildfire			Harvest			Non-stand replacing			Road and infrastructure		
Ecozone	Total AGB (Pg)	Annual rate of AGB ($Tg \cdot yr^{-1}$)	Annual rate of AGB density ($Mg \cdot yr^{-1} \cdot ha^{-1}$)	Total AGB (Pg)	Annual rate of AGB ($Tg \cdot yr^{-1}$)	Annual rate of AGB density ($Mg \cdot yr^{-1} \cdot ha^{-1}$)	Total AGB (Pg)	Annual rate of AGB ($Tg \cdot yr^{-1}$)	Annual rate of AGB density ($Mg \cdot yr^{-1} \cdot ha^{-1}$)	Total AGB (Pg)	Annual rate of AGB ($Tg \cdot yr^{-1}$)	Annual rate of AGB density ($Mg \cdot yr^{-1} \cdot ha^{-1}$)
Atlantic Maritime	0.002	0.051	1.22	0.093	2.993	0.99	0.017	0.549	1.13	0.004	0.123	0.93
Boreal Cordillera	0.014	0.45	0.20	0.003	0.112	0.61	0.014	0.461	0.51	0.001	0.019	0.40
Boreal Plains	0.067	2.153	0.45	0.076	2.457	1.01	0.044	1.433	0.91	0.008	0.266	0.80
Boreal Shield East	0.024	0.781	0.23	0.166	5.358	0.71	0.021	0.674	0.31	0.009	0.28	0.73
Boreal Shield West	0.131	4.226	0.36	0.058	1.886	0.89	−0.001	−0.033	−0.01	0.002	0.058	0.79
Hudson Plains	0.013	0.435	0.31	0.001	0.034	0.78	0.027	0.873	0.75	0.0003	0.01	0.78
Montane Cordillera	0.013	0.425	0.47	0.162	5.218	1.26	0.081	2.621	1.23	0.009	0.276	1.25
Pacific Maritime	0.003	0.088	1.75	0.085	2.738	2.40	0.013	0.431	1.48	0.005	0.155	1.67
Taiga Cordillera	0.005	0.153	0.25	0.0003	0.009	0.18	0.002	0.067	0.25	0.00007	0.002	0.20
Taiga Plains	0.059	1.898	0.37	0.010	0.327	1.48	0.014	0.466	0.66	0.001	0.039	0.93
Taiga Shield East	0.01	0.336	0.16	0.0003	0.01	0.49	0.021	0.665	0.27	0.0002	0.006	0.41
Taiga Shield West	0.028	0.917	0.14	0.0002	0.006	0.41	−0.0001	−0.004	−0.01	0.00002	0.001	0.42
Canada's forested ecosystems	0.369	11.914	0.31	0.656	21.148	1.01	0.254	8.203	0.54	0.038	1.234	0.90

Table 7. Aboveground biomass (AGB) dynamics in newly treed areas for the period 1984–2016, by forested ecozone and for the entirety of Canada's forested ecosystems.

Ecozone	Newly treed area (Mha)	Total ABG (Pg)	Annual rate of AGB ($Tg \cdot yr^{-1}$)	Annual density rate of AGB ($Mg \cdot ha^{-1} \cdot yr^{-1}$)
Atlantic Maritime	2.27	0.205	6.395	2.82
Boreal Cordillera	5.65	0.371	11.593	2.05
Boreal Plains	7.29	0.679	21.219	2.91
Boreal Shield East	9.37	0.609	19.018	2.03
Boreal Shield West	7.84	0.491	15.337	1.96
Hudson Plains	4.14	0.119	3.727	0.90
Montane Cordillera	4.16	0.549	17.163	4.13
Pacific Maritime	1.35	0.262	8.200	6.07
Taiga Cordillera	1.95	0.082	2.578	1.32
Taiga Plains	6.83	0.385	12.036	1.76
Taiga Shield East	6.21	0.207	6.471	1.04
Taiga Shield West	3.99	0.130	4.067	1.02
Canada's forested ecosystems	61.05	4.090	127.801	2.09

While the total area impacted by a particular disturbance is one method to characterize the relative importance of that disturbance in understanding forest dynamics, the net loss or gain of treed AGB provides a complementary indicator by which the relative impact of disturbances can be measured. The relative impacts of harvest and wildfire on Canada's forest ecosystems over the period considered herein have been documented (White *et al* 2017, Hermosilla *et al* 2019). For example, while the rate of harvesting has been relatively consistent over time, wildfires are much more stochastic, with the annual area impacted by wildfire fluctuating markedly from year to year (White *et al* 2017). The results of our analysis indicate that total AGB losses attributable to wildfire (−1.79 Pg) and harvesting (−1.726 Pg) were similar (table 5) and yet wildfires impacted approximately twice as much treed area as harvesting (table 1). Moreover, we found that the rate of AGB density loss for harvesting (−2.57 Mg yr^{-1} ha^{-1}) was 1.5 times that of wildfire (−1.43 Mg yr^{-1} ha^{-1}). Whereas fires are undiscriminating and impact a broad range of forest conditions and vegetation types, commercial timber harvesting typically occurs on more productive, accessible, and southerly forest sites, and will specifically target the removal of mature, merchantable trees with high AGB.

Likewise, the rate at which vegetation returns following disturbance also varies by disturbance type. White *et al* (2017) reported that 78.6% of areas in Canada impacted by timber harvesting experienced spectral recovery (i.e. return of vegetation) within 10 or fewer years, compared to only 35.5% of areas impacted by wildfire. Herein, we found that harvested areas (1.01 Mg yr^{-1} ha^{-1}) accrued biomass at a rate that was triple that of areas impacted by fire (0.31 Mg yr^{-1} ha^{-1}), again reflecting the higher productivity environments within which harvesting typically occurs, and accounting for policies that mandate the regeneration of forests following harvests (Haddon 1997). Such policy prescriptions for regeneration have not been applied to areas impacted by wildfire. These differences in the rates of biomass accrual post-disturbance echo the spectral recovery trends reported in White *et al* (2017) and Matasci *et al* (2018b).

In this study, we also included stand-replacing disturbances typed to roads and infrastructure. We have not reported on this change type, as it is often sub-pixel and not consistently detectable at the 30 m spatial resolution of the Landsat data used (Hermosilla *et al* 2015b). Moreover, in some of Canada's managed forests, temporary roads are constructed to enable harvesting operations, and these roads are subsequently decommissioned once harvesting is complete. As a result, capture of roads and infrastructure as reported may therefore be incomplete and necessitate the use of higher spatial resolution data (e.g. Sentinel-2) to further account for the short and long-term biomass consequences of roads and infrastructure. In reality however the biomass consequences of roads and infrastructure for Canada's forested ecosystems for 1984–2016 were relatively small (−0.099 Pg; table 5, figure 4) compared to the other disturbance types.

Despite the spatial extent of non-stand replacing disturbances on treed vegetation (e.g. insects, drought stress; table 1), non-stand replacing disturbances resulted in a comparatively small amount of AGB loss (−0.325 Pg) for the period 1985–2016. These results are in keeping with the characteristics of this disturbance type: typically, non-stand replacing disturbances represent a change in vegetation condition and not a change in land cover (Hermosilla *et al* 2019). For example, a defoliating insect may cause a temporary change in canopy cover that may be recovered within the same season, whereas an insect such as the mountain pine beetle can cause widespread mortality; however, the AGB consequences will be very gradual, unless the impacted forests are subjected to salvage harvesting or wildfire. The difficulty in interpreting non-stand replacing disturbances is echoed by Kennedy *et al* (2018), where the wide-range of drivers that can result in time series detection (described by Cohen *et al* (2016) as decline) are difficult to attribute and, as a result, are noted to be have high uncertainty in biomass impacts.

Over the analysis period, newly treed areas are identified, accounting for 4.09 Pg of biomass. These areas are largely a function of disturbance that occurred prior to our baseline year (1984), with these areas becoming treed following successional processes. With increasingly long time series to inform on disturbance and the return of forest vegetation to these previously disturbed lands, there will be less opportunity for the presence of lands with an ambiguous disturbance history. Over time there will be a diminishing opportunity for newly treed areas (pre-baseline change) because new disturbances will be captured in the satellite record. Additional and focused spatial analysis to determine the nature and distribution of newly treed areas not associated with prior disturbance requires attention.

In complementary research, Kennedy *et al* (2018) highlight the need for combining biomass for a specific time with the disturbance process driving the change for understanding dynamics. This regional research also brings together times series from Landsat and imputation to estimate biomass. The authors point out the role of methodological choices as influencing uncertainty, with allometric equations to estimate biomass from tree data exceeding the uncertainty from remote sensing and related modeling. The authors caution in using biomass values at the 30 m grain of Landsat and highlight the agreement over more broad scales. Kennedy *et al* (2018) utilized a Landsat-derived time series change data set with additional attribution of temporal agents of change pointing to future opportunities for refinement and expansion of our change categories. Given appropriate training and validation data, a nested and expanded change hierarchy is in place and suitable for implementation (Hermosilla *et al* 2015b) to offer additional change agent and process richness in future work.

From knowledge of historic biomass dynamics, desired projections of future conditions can be informed. The biomass development trends reported here are based upon the then, now historic, prevailing environmental and climatic conditions. Longer-term forest structure and growth characteristics arising following disturbance can be expected to differ from those past and current conditions (Apps *et al* 1993). Future projections of total biomass in Canada are expected to be difficult to make due to role of highly variable natural disturbances (Kurz *et al* 2008b).

5. Conclusions

The estimation of biomass from time series remotely sensed data and modeling provides spatially-explicit insights on aboveground biomass dynamics at management-relevant spatial scales and over science-relevant temporal periods. The spatially-explicit nature of the AGB time series used herein allows for flexibility in reporting and analysis, while the annual AGB estimates enable detailed investigations of the relative losses and gains in treed AGB over time. Disentangling the consequences of disturbances in terms of the area impacted versus AGB losses improves our understanding of AGB dynamics, while additionally accounting for the important role of long-term biomass accrual in undisturbed forests.

Canada has a large forested land base that is shaped by both natural and anthropogenic disturbances. Time series mapping of forest change indicates that generally <1% of forested ecosystem area in Canada is disturbed annually, with the key stand-replacing disturbance agents being wildfire and harvesting (White *et al* 2017). Our results indicate that although wildfire impacts larger areas, the total AGB consequences of forest harvesting and wildfire are similar. Likewise, harvesting affects 1.3 times more area than non-stand replacing disturbances but the total AGB consequences are five time less than that of harvest, as non-stand replacing disturbances are related to a change in vegetation condition and not in land cover.

In conjunction with knowledge of when, where, and what type of change has occurred, valuable insights on AGB dynamics, well beyond a periodic snapshot, can be captured. Historically, remote sensing was used to find change, often via differencing of images representing two dates. These approaches would provide for a limited area of undifferentiated information on change, largely in the form of depletions. Now using time series of free and open satellite imagery, disturbances can be captured and typed. Calibrated radiometry then allows for the development of algorithmic approaches to estimate forest structure for current and historic conditions in a spatially-explicit fashion. Knowledge of biomass status and dynamics over large areas in a spatially-explicit manner supports reporting and modeling as well as providing an otherwise unavailable source of information to inform projections of future structural conditions. While the findings herein are focussed upon Canada, the Landsat data used are available globally in a free and open access form, enabling portability of implementation.

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Data availability statement

The data that support the findings of this study will be openly available following a delay.

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