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

Michael A Wulder, Txomin Hermosilla, Joanne C White and Nicholas C Coops

1 Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5, Canada
2 Integrated Remote Sensing Studio, Department of Forest Resources Management, University of British Columbia, 2424, Main Mall, Vancouver, British Columbia V6T 1Z4, Canada

E-mail: mike.wulder@canada.ca

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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, Zolko 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 Columbia), 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 ecozones 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.
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.
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 2018)), 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.

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

| Ecozone                | Area  | 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                          | 352 683                          |
| Boreal Shield East     | 107 710 345 | 37 577 640 | 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 | 4 415 154       | 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  | 1 129 050        | 292 089                            | 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      | 7 298 422 | 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                      |

### 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...
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 Mg·yr\(^{-1}\)·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 Tg·yr\(^{-1}\)), as well as the annual rate of AGB density accrual or loss (in Mg·yr\(^{-1}\)·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 regrowth 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 · 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 (1998)                           | 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 · yr⁻¹) | Annual AGB density accrual (Mg · ha⁻¹ · 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     | 7.66                                    | 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 · ha⁻¹) and Montane Cordillera (128.21 Mg · 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 · ha⁻¹) and Hudson Plains (30.51 Mg · 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...
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.

| Ecozone                  | Disturbed areas | Post-disturbance regrowth | Ongoing disturbances |
|--------------------------|-----------------|----------------------------|----------------------|
|                          | Area (Mha)      | Total AGB (Pg)             | Annual rate of AGB loss (Tg · yr⁻¹) | Annual rate of AGB density loss (Mg · yr⁻¹ · ha⁻¹) | Total AGB (Pg) | Annual rate of AGB accrual (Tg · yr⁻¹) | Annual rate of AGB density accrual (Mg · yr⁻¹ · 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<sup>-1</sup>) | Total AGB loss (Pg) | Annual rate of AGB loss (Tg yr<sup>-1</sup>) | Total AGB loss (Pg) | Annual rate of AGB loss (Mg yr<sup>-1</sup> ha<sup>-1</sup>) | Total AGB loss (Pg) | Annual rate of AGB loss (Mg yr<sup>-1</sup> ha<sup>-1</sup>) | Total AGB loss (Pg) | Annual rate of AGB loss (Mg yr<sup>-1</sup> ha<sup>-1</sup>) |
| 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                |
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
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.

| Ecozone               | Wildfire          | Harvest          | Non-stand replacing | Road and infrastructure |
|-----------------------|-------------------|------------------|----------------------|-------------------------|
|                       | Total AGB (Pg)    | AGB density (Mg · yr⁻¹ · ha⁻¹) | Total AGB (Pg) | AGB density (Mg · yr⁻¹ · ha⁻¹) | Total AGB (Pg) | AGB density (Mg · yr⁻¹ · ha⁻¹) | Total AGB (Pg) | AGB density (Mg · yr⁻¹ · 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 |
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

| Ecozone                | Newly treed area (Mha) | Total AGB (Pg) | Annual rate of AGB (Tg·yr⁻¹) | Annual density rate of AGB (Mg·ha⁻¹·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                                     |
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.

ORCID iDs

Michael A Wulder https://orcid.org/0000-0002-6942-1896
Txonm Hermosilla https://orcid.org/0000-0002-5445-0360
Joanne C White https://orcid.org/0000-0003-4674-0373
Nicholas C Coops https://orcid.org/0000-0002-0151-9037

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