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Climate Change and Disturbance Are Driving Systematic Shifts in Forest Composition and Cover Across Canada and Alaska

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Abstract. Forests in Canada and Alaska are being altered by climate change and disturbance. However, the nature, magnitude, and geography of these changes are poorly understood. Here, we use time series of remotely sensed imagery to show that 9.4 x 10^5 km^2 (equivalent to nearly 11 per cent) of forests in Canada and Alaska experienced changes in land cover between 1986 and 2020. The area occupied by needleleaf forests decreased, while broadleaf forests and shrublands expanded. Needleleaf forest loss was most prevalent in taiga forests where shrub cover has expanded, while gains in broadleaf forests were concentrated in warmer and moister regions. Land cover transitions after disturbance reveal climate- and ecoregion-specific recovery patterns that explain the expansion of broadleaf forests and shrubs that we observe. Our results provide evidence that climate change and disturbance are driving systematic shifts in forest and shrub cover across large expanses of Canada and Alaska.

1 Introduction

Temperate and boreal forests play an important role in the global carbon budget, are tightly coupled to the climate system (Bonan et al., 1992; Chapin III et al., 2000; Randerson et al., 2006), and are experiencing rapid warming (Previdi et al., 2021; Rantanen et al., 2022). Timber harvest and fire are the dominant disturbances (Baltzer et al., 2021; Bond-Lamberty et al., 2007), and there is substantial evidence that fires are becoming more frequent and severe in temperate and boreal forests (De Groot et al., 2013; Jones et al., 2024; Kasischke and Turetsky, 2006; Wang et al., 2025; Zhao et al., 2024). In 2023 alone, fires burned about 15 × 10^6 ha in Canada; more than double the previous record and more than seven times the long-term average (Jain et al., 2024). The combined effects of ongoing changes in climate and disturbance regimes have the potential to fundamentally alter the structure, function, and plant functional type (PFT) composition of boreal forests (Gauthier et al., 2015; McDowell et al., 2020; Rotbarth et al., 2025; Scheffer et al., 2012; Turner and Seidl, 2023). Because PFT composition influences surface energy and radiation budgets, a systematic shift in the composition of temperate and

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boreal forests has the potential to drive large-scale changes in the high-latitude climate system (Bonan, 2008; Bond-Lamberty et al., 2007; Mack et al., 2021; Mekonnen et al., 2019; Randerson et al., 2006; Rogers et al., 2013; Swann et al., 2010). Equally important, disturbance-induced transitions from coniferous to deciduous forests can alter the continental scale net ecosystem carbon balance, with the release of carbon from vegetation and soils from combustion and decomposition partially offset by higher rates of photosynthesis (Goulden et al., 2011; Kim et al., 2024; Welp et al., 2007; Zimov et al., 1999), increased aboveground carbon storage (Mack et al., 2021), and reduced carbon loss from wildfire (Black et al., 2026).

Ecoregions with tree cover occupy 8.2×10^6 km^2 in Canada and Alaska, of which roughly three quarters is boreal forest. These ecosystems are dominated by forests with a wide range of tree cover, but include a mix of land cover types, are highly adapted to disturbance, and are resilient to stand-replacing fires (Bond-Lamberty et al., 2007; Foster et al., 2022; Johnstone et al., 2010, 2016; Macias Fauria and Johnson, 2008). However, as the climate of Canada and Alaska has become warmer and drier, accompanied by more frequent ignition events from lightning, fires are becoming more frequent and more intense (Foster et al., 2022; Veraverbeke et al., 2017; Wang et al., 2025; Whitman et al., 2019). Severe fires can burn deeply into organic soil layers, which are common in boreal forests, and increase the likelihood of deciduous broadleaf forest (DBF) seedling establishment in moderate to well-drained areas (Johnstone et al., 2020; Walker et al., 2019, 2023). In addition, warmer and drier soils during mid-summer, or repeat wildfires over short timescales (Coop et al., 2020), can curtail growth and increase mortality in black spruce seedlings (Baltzer et al., 2021; Johnstone et al., 2016), decreasing resilience to wildfire. Consistent with this, several recent studies have suggested that the post-fire regeneration pathway of evergreen needleleaf forests (ENF) in boreal North America is changing to favor the establishment of broadleaf species (Baltzer et al., 2021; Mack et al., 2021; Walker et al., 2023), and that changing fire regimes and climate warming have the potential to fundamentally alter the age structure and species composition of Canadian and Alaskan forests towards younger forests with more deciduous species (Mekonnen et al., 2019; Reich et al., 2022). However, the nature, magnitude, and geography of these changes at continental scale are poorly understood and characterized.

Satellite imagery provides a robust basis for mapping changes in forest cover over large areas (Hansen et al., 2013; Hermosilla et al., 2018, 2022; Wang et al., 2020). Despite this, recent remote sensing-based studies focusing on changes in Canadian and Alaskan forests have drawn different conclusions (Hermosilla et al., 2025; Massey et al., 2023; Potapov et al., 2008; Wang et al., 2020) regarding if and how these forests are changing. Furthermore, in addition to drawing different conclusions related to changes in area and composition, results from some of these studies also disagree with results from field-based studies regarding if and how the area and composition of forests in Canada and Alaska are being altered by disturbance and climate change. As a result, improved understanding regarding if, how, where, and by how much forest area and composition are changing is urgently needed.

To address this knowledge gap, we used medium-spatial resolution (30 m) satellite imagery from Landsat to map, quantify, and attribute changes in forest and other land cover types across forested ecosystems in Canada and Alaska from 1986 to 2020 (see Methods). Using machine learning, we combined Landsat imagery with extensive National Forest

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Inventory data (over 8×10^5 plots) to develop a robust methodology that is specifically designed for forest cover change detection and mapping. A large and independent reference data set (n = 2,043) allowed us to rigorously quantify uncertainties and correct for error-induced bias in our maps (Olofsson et al., 2014). Our results provide three novel and important findings that contribute new information and understanding regarding how forest and land cover have been altered by climate change and disturbance in Canada and Alaska. First, our maps provide a detailed and spatially explicit quantification of the nature, magnitude, and biogeography of systematic changes in forest cover (notably, ENF loss and DBF gain) over 35 years that is not available from field studies and that has not been previously identified from remote sensing with high accuracy. Second, our results identify ecoregion-specific variability in successional pathways that explain the long-term changes in forest cover that we identify. Third, our analysis reveals biogeographic patterns of ENF loss and DBF expansion that are consistent with a geographic shift in the climate suitability for ENF and DBF in Canada and Alaska.

2 Methods

2.1 Study Area, Ecoregions, Fire Perimeters, and Timber Harvest Data

The study area encompassed all forested ecoregions of boreal Canada and Alaska and includes about 8.2×10^6 km^2 (Figure. 1). To delineate our study region, we combined ecoregion boundaries from the EPA North America Level II Ecoregions with boundaries from the Terrestrial Ecozones of Canada. The resulting map included 7 ecoregions spanning all forested ecoregions in Canada and Alaska (Figure 2). This approach follows the same basic framework that was used by Baltzer et al. (Baltzer et al., 2021) and Massey et al. (Massey et al., 2023), with two key differences. First, we included all areas included in the US EPA Level II Northern Forests ecoregion located within Canada. Inclusion of these areas expands the study region to include southern boreal and temperate forests in Eastern Canada that were not included in Baltzer et al. (and Massey et al. (. Second, we included forests in the US EPA Level II Marine West Coast ecoregion located within Canada and Alaska.

Fire history data was obtained from the Canadian National Fire Database, which includes perimeters for fires dating back to 1919, depending on the province. For Alaska, we used the Alaska Fire History Perimeter Polygon data set (Alaska Wildland Fire Coordinating Group (AWFCG)) from the Alaska Interagency Coordination Center (AICC), which includes fire polygons starting in 1947. Because the sample size, accuracy and reliability of fire perimeters is lower early in the time series, we restricted our analyses to exclude fire events that occurred more than 60 years prior to the most recent fire event at each pixel according to the Alaskan and Canadian fire databases. Note that our Landsat-derived land cover and forest cover change maps include unburned islands located inside fire polygon perimeters. We confirmed the realism of these islands by comparing our results with independently generated maps of disturbed areas from Landsat (Zhang et al., 2022). Areas that experienced timber harvest were derived from annual maps of timber harvest (Hermosilla et al., 2016), which cover all of Canada for 1985 to 2020. Harvest data is not available for Alaska.

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2.2 Landsat Imagery

We used 39 years of 30 m multispectral imagery collected by the Thematic Mapper, Enhanced Thematic Mapper, and Operational Land Imager onboard Landsat 5, 7 and 8, respectively. Specifically, we used atmospherically corrected surface reflectance imagery included in the USGS Collection 2 Landsat archive. To perform land cover mapping, we used all available observations at each pixel spanning the period 1984-2022, excluding reflectance values contaminated by clouds, cloud shadows, or snow according to quality assurance information included with the USGS Collection 2 Landsat data set. Mapping was performed at 30 m spatial resolution across all years and encompassed all Landsat pixels located inside forested ecoregions of Canada and Alaska, as defined above.

2.3 Land Cover and Land Cover Change Mapping

We mapped seven broad land cover classes (Table S7). The foundation of our mapping methodology is the Continuous Change Detection and Classification (CCDC) algorithm (Zhu and Woodcock, 2014). The CCDC algorithm uses harmonic models fit to the time series of Landsat multispectral reflectance at each pixel. This approach includes explicit treatment of sub-annual seasonality and provides a natural way to gap-fill missing data and filter noisy observations, which are common at high latitudes where missing data and contamination from clouds are common. To enable processing of the Landsat archive at the continental scale, we used the implementation of CCDC available on Google Earth Engine, where we performed all of our mapping (Earth Engine Data Catalog, 2020). CCDC results at each pixel tend to be less reliable at the beginning and end of the time series. Hence, to avoid errors and artifacts, we excluded mapping results from the first two and last two years of the time series at each pixel. The results yielded annual maps of land cover and land cover change for 1986-2020 (35 years) spanning all forested ecoregions of North America.

Mapping was performed at the ecoregion scale, where unique classification models were estimated for each ecoregion, using the 12 ecoregions included in the Level II USA ecoregions of North America (Figure S8). To eliminate artifacts along the boundaries of adjacent ecoregions, training data from 100 km buffers in all adjacent ecoregions were included in the training set for each ecoregion-specific classification model. Mapping was performed using the random forest algorithm (Breiman, 2001), a supervised classification algorithm, and the models were trained using Landsat spectral features derived from CCDC along with tasseled cap spectral vegetation indices and gridded data related to human settlements, climate, surface water, and topography (Table S8 provides a complete list of input features, along with details).

2.4 Training Data

Training data used to create random forest models were derived from two sources. In Canada, we used a stratified random sample of training sites extracted from the Canada National Forest Inventory (NFI) Photo Plot data set, which provides high-quality photo-interpreted land cover attributes from high-resolution imagery (Falkowski et al., 2009; Leckie and Gillis, 1995) (Figure S7). Each photo plot consists of a 2 by 2 km (400 ha) area. The entire NFI data set provides a 1% sample of the

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target population in Canada's National Terrestrial Monitoring Framework (NTMF), in which plot locations are allocated using a systematic 20 by 20 km sampling grid. The survey is conducted every 10 years and follows a hierarchical classification structure that includes land cover and vegetation density classes, along with information regarding land use, ownership, and protected status. The total data set includes roughly 397,000 polygons.

For this work, we randomly selected individual Landsat pixels located in NFI polygons (ensuring a minimum distance of 45 m from the edge of the polygon) using the NFI Photo Plot '1st remeasurement' data set, which covers all of Canada. A minimum of 2,000 points were selected for each class. In total, 52,228 pixel-based training samples were selected from the NFI photo plot data set. To ensure that imbalance in the class frequency distribution of training data for each ecoregion did not introduce bias to random forest classification results, we augmented training data for any class that represented less than 5% of the total sample within an ecoregion by adding randomly selected training points from adjacent ecoregions. Conversely, if the sample size for a particular class exceeded 30% of the total training data set within an ecoregion, we down sampled the training data for that class to limit the number of samples to be 30%, increasing the sample from other classes proportionally. In western Canada and Alaska, we supplemented the NFI-based training data with 6,409 sites from Wang et al. (Wang et al., 2020) for bare, shrub, and herbaceous classes, which we cross-walked from the barren, low shrub, tall shrub, open shrubs, and herbaceous classes in their study. We also added 2,404 herbaceous training sites that were randomly selected from the Global Cropland Expansion in the 21st Century data set compiled at the University of Maryland (Potapov et al., 2021), using pixels that were labelled as cropland during the entire time period in this product. To balance the training samples from Wang et al. (Wang et al., 2020), which were only available for the NASA ABoVE study region in Northwestern North America, and from the UMD product, which we only used in the Prairie ecoregion in Western Canada, we supplemented the random sample of NFI polygons in Eastern Canada with additional samples of bare, shrub, and herb from NFI polygons, excluding NFI polygons that overlapped with cropland pixels based on the UMD cropland data layer. To improve the quality of our training data, we implemented a machine learning-based cross validation procedure to filter out low quality data (See Supplementary Info Section 1).

2.5 Accuracy Assessment and Unbiased Area Estimation

To provide unbiased estimates of land cover change areas and to quantify uncertainty in these estimates, we compiled a high-quality reference data set based on a probability sample design following community standard practices, as described by (*48*). Using this approach, we computed estimates for the area of land cover and forest cover changes after accounting for classifier bias. For reasons we describe above, we selected 1986 and 2020 as the beginning and end of our time period for reference data sampling. We specified a target standard error for overall accuracy of 1% (equivalent to 4,264 km^2, or a 95% confidence interval of ± 8,528 km^2). In support of this target, we drew a probability sample of 2,043 reference points using 7 stable land cover and 6 land cover change strata (Table S7). We excluded the ice/snow class in the accuracy assessment because it is not the focus of this work. The change classes are mutually exclusive and are based on the status of each pixel at the beginning and end of the time series. Table S3 provides a matrix illustrating stable land cover and land cover change

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classes between 1986 and 2020. For each reference point, land cover and land cover change labels were assigned based on visual interpretation using high-resolution imagery and time series of spectral reflectance and vegetation index time series for each sample point. The overall accuracy of our stable land cover and land cover change map (7 classes) was 79% ± 0.02 (Table S9). Note that the confidence intervals shown in Fig.1 are estimated based on the assumption that uncertainty does not vary across years.

3 Results

3.1 Disturbance-Driven Changes in ENF versus DBF

Excluding Arctic and alpine tundra zones, 9.4×10^5 km^2 (10.9 ± 2.2%) of Canada and Alaska experienced land cover change between 1986 and 2020 (Figures 1 and S1; Tables 1 and 2). Total forest cover, including ENF and DBF, decreased by 1.4×10^5 km^2 (3.4%) during the study period. Transition of ENF to non-forest land cover was the primary driver of this decrease, encompassing 4.5×10^5 km^2. After accounting for areas of ENF gain, which include areas of regrowth from disturbance events that occurred before 1986, the area occupied by ENF decreased by 3.2×10^5 km^2, a net loss of 9.4% over the 35-year study period. During the same period, the area occupied by DBF and shrublands increased by 1.8×10^5 km^2 (21.5%) and 1.6×10^5 km^2 (17.1%), respectively, equivalent to 75.7% of the area of ENF loss. In areas with stable land cover, ENF occupied 32.9 ± 1.2% of the study area, followed by DBF (9.7 ± 0.8%), shrublands (13.0 ± 1.1%), and herbaceous vegetation (10.0 ± 0.8%) (Table S1).

The type and extent of forest cover changes varied across seven broad ecoregions (Figures 2 and S2). Forest cover change, particularly ENF loss, occurred in all ecoregions of the study area during the study period, but the area, nature, and intensity of changes varied by latitude and ecoregion (Figure 2). ENF loss was concentrated in taiga forests located in northern areas of the boreal forest, and was most extensive in the Shield East, Shield West, and Plains West ecoregions, each of which had losses of ENF greater than 50×10^3 km^2 (Figures 2 and S3). As a proportion of total change, ENF transitions to other non-forested classes constituted the largest proportion of change in 5 out of 7 ecoregions and accounted for nearly 50% of all land cover change in the Shield West ecoregion (Figure 2c). DBF, on the other hand, expanded in all seven ecoregions, particularly in the Shield East and Shield West ecoregions, which together accounted for 54% of all DBF gain.

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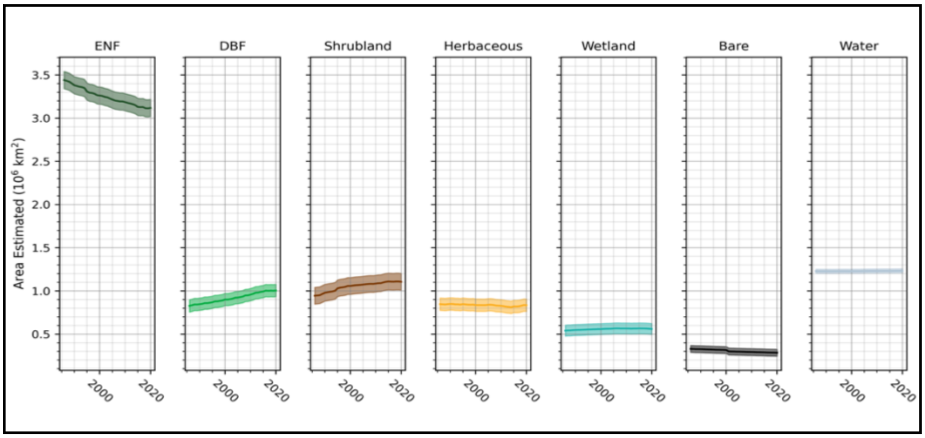

Figure 1. Changes in land cover in boreal and temperate ecoregions of Canada and Alaska between 1986 and 2020. Total forest cover (ENF + DBF) decreased during the study period, driven by the loss of ENF. Color bands show approximate 95 percent confidence intervals on the annual area estimates (see Methods).

Land Cover Change	**Area (10^6 km^2)**	**Percent of study domain**
Evergreen needleleaf forest (ENF) loss	0.45 ± 0.05	5.2%
Deciduous broadleaf forest (DBF) gain	0.21 ± 0.05	2.4%
Evergreen needleleaf forest (ENF) gain	0.15 ± 0.04	1.7%
Deciduous broadleaf forest (DBF) loss	0.04 ± 0.01	0.5%
Shrubland gain	0.05 ± 0.02	0.6%
Other	0.04 ± 0.02	0.5%
Total	0.94 ± 0.19	10.9%

Table 1. Changes in the area occupied by land cover types in Canada and Alaska between 1986 and 2020. Areas shown are mutually exclusive of changes in the other classes, e.g., ENF (DBF) loss is the total area where ENF (DBF) in 1986 was converted to non-forested land cover by 2020. ENF (DBF) gain is the area occupied by ENF (DBF) in 2020 that was a different land cover class in 1986. Shrubland gain includes areas occupied by water, wetlands, herbaceous, or bare land cover in 1986. Uncertainty in the estimated annual land cover area for each class is shown as 95% confidence intervals. Only classes showing statistically significant changes are included.

Land Cover Type	Area in 1986 (10^6 km^2)	Area in 2020 (10^6 km^2)	Area of Change (10^6 km^2)	% Change
Bare	0.329	0.284	-0.044	-13.5%
Deciduous broadleaf forest (DBF)	0.827	1.005	0.178	21.5%
Evergreen needleleaf forest (ENF)	3.441	3.119	-0.322	-9.4%
Herbaceous	0.847	0.834	-0.013	-1.5%
Shrubland	0.944	1.106	0.162	17.1%
Water	1.229	1.234	0.005	0.4%
Wetland	0.541	0.560	0.019	3.4%
Total Forested Area	4.268	4.124	-0.144	-3.4%

Table 2. Total area occupied by major land cover classes, change in the area occupied by each class, and the percentage change in each class between 1986 and 2020, relative to 1986. Total forested area is the combined area of ENF and DBF. Unlike Table 1, net area changes include transitions between classes, and therefore are not mutually exclusive (e.g., the area of change in ENF includes conversion to DBF, which is also included in the total change in DBF area). Note, the total mapped area decreased by < 0.2% between 1986 and 2020 due to the rounding errors, changes in the area of permanent ice and snow (not shown), and low-quality Landsat observations that are removed each year (see Methods).

Recent results have suggested that disturbance from wildfires and timber harvest explain large-scale land cover changes in northwestern North America (Wang et al., 2020). To quantify the role of disturbance in the changes in forest cover that we identify across all of Canada and Alaska, we intersected our land cover change map with maps of timber harvest from Canada's National Terrestrial Ecosystem Monitoring System (NTEMS) (Hermosilla et al., 2016) and fire perimeter data from the Canadian Forest Service, the Alaska Wildland Fire Coordinating Group (AWFCG), and the Alaska Interagency Coordination Center (AICC). Consistent with results from Wang et al. (Wang et al., 2020), roughly two-thirds of ENF loss (3.27×10^5 km^2, 68.0%) occurred in locations that experienced disturbance from fire during the study period (Tables 3 and S2). Furthermore, a substantial proportion of locations where ENF and DBF increased (6.70×10^4 km^2 = 22.3%; 3.73×10^4 km^2= 13.3%, respectively) were located in areas where fire occurred before the Landsat satellite record (i.e., prior to 1984), reflecting recovery and succession from these prior disturbances. Roughly half of the area where DBF expanded was previously occupied by ENF (Table S3, S4). Timber harvest accounted for 11.8% (5.7×10^4 km^2) of the total area of ENF loss, 1.6% (4.7×10^3 km^2) of the total area of ENF gain, and was collocated with 17.3% of the area experiencing expansion in DBF (Table S5). The loss of DBF in harvested areas likely reflects the inclusion of Mixed Forests in our DBF class. Hence, the role of timber harvest, while important, was secondary to the role of fire in explaining patterns of ENF loss and DBF gain.

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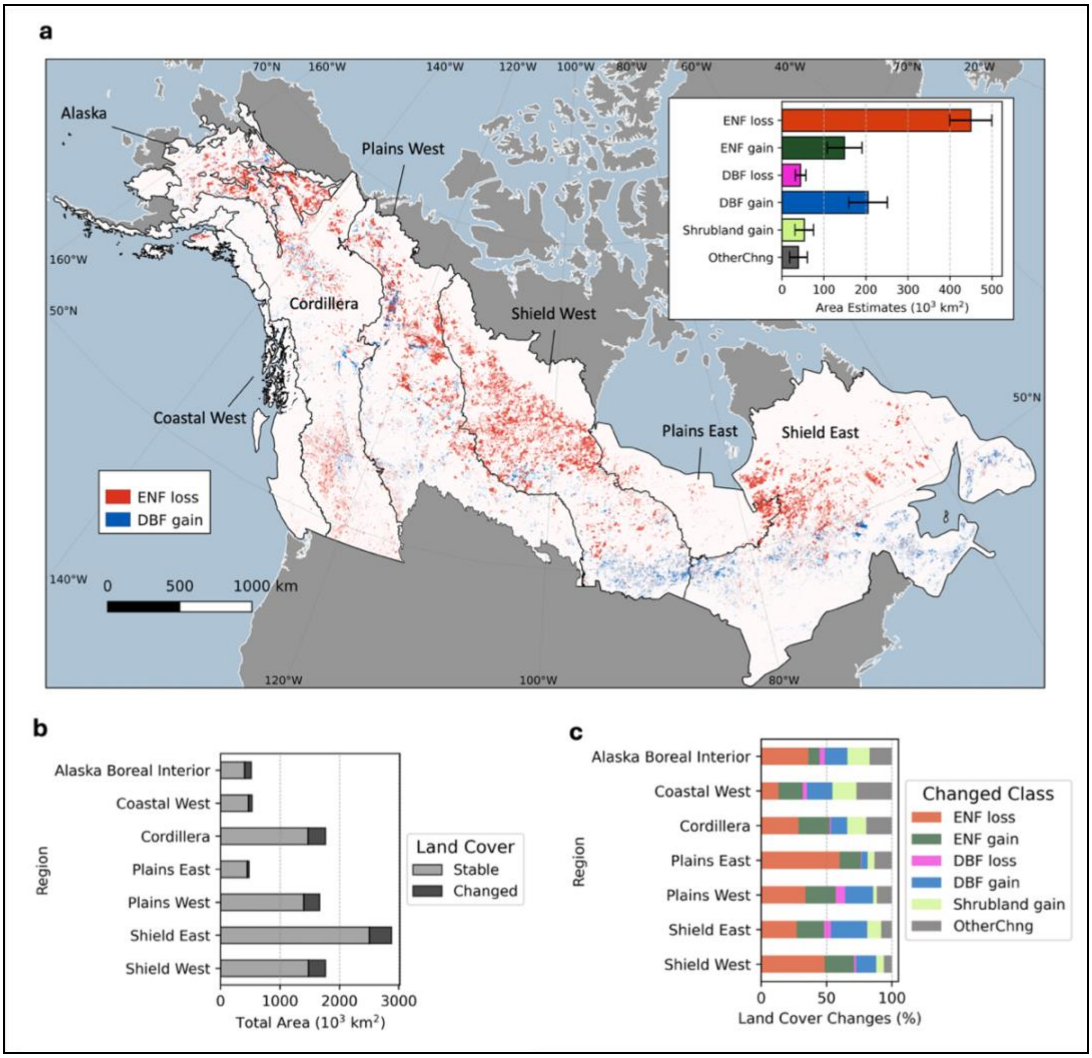

215 **Figure 2. Geographic distribution of forest and land cover change in Canada and Alaska from 1986-2020**. Areas of ENF loss shown in red (a) identify locations where ENF has been converted to non-forest land cover and is concentrated in northern areas of the Shield East, Shield West, Plains West, and Alaska Boreal Interior ecoregions occupied by taiga forests. Roughly half of the area mapped DBF as gain (shown in blue) is in locations previously occupied by ENF and is concentrated in temperate and southern regions of the boreal forest. Panels (b) and (c) show the area and proportional changes, respectively, in land cover for each ecoregion.

3.2 Changing Successional Pathways After Fire

To evaluate how successional processes, and changes therein, are captured by the land cover changes that we mapped, we used timber harvest data from Canada and fire perimeter data from Canada and Alaska to stratify results from our change analysis into 10-year age-cohorts following disturbance. We analyzed these changes for all of Canada and Alaska and for each ecoregion, including all pixels that were disturbed by fires or harvests (about 1.7×10^6 km^2). To allow for longer-term

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successional dynamics arising from disturbance that occurred prior to the Landsat record while also recognizing that the accuracy of fire perimeters decreases earlier in the record, we examined PFT changes up to 60 years after disturbance, using 10-year cohorts.

Results from this analysis identify land cover changes after fire that are consistent with ecoregion-specific changes in the successional pathway of forests in Canada and Alaska (Figures 3, S4, and S5; Tables 3 and S6). Ten years after fire events, the proportional area of ENF in disturbed locations decreased by about 50% (or more) in each ecoregion, with ENF mostly replaced by herbaceous and shrubland cover. Residual ENF areas in the first time cohort after disturbance reflect islands of unburned forest located inside fire perimeters and uncertainty in the location of older fire perimeters (Meddens et al., 2018) (cf. Figure S6). In subsequent time periods, forest cover increases, but with distinct patterns in different ecoregions. In three ecoregions (Coastal West, Cordillera, Plains East), the proportion of ENF recovers to pre-fire levels after 60 years. In the other four ecoregions the proportion of ENF declines and the proportion of DBF increases relative to their pre-fire state. These results are consistent with recent results that have documented similar shifts in the PFT composition of North American Boreal Forests after fires (Baltzer et al., 2021; Kim et al., 2024; Wang et al., 2020). Our results also identify increases in the fractional area occupied by wetlands directly after fires in the Plains East (which includes the Hudson Bay lowlands) and Plains West ecoregions. This change is transient in the Plains East ecoregion, which has relatively low area and frequency of disturbance, with wetlands returning to ENF. In the Plains West ecoregion, however, areas of wetland expansion after fires are gradually replaced by DBF. This latter result may be related to permafrost thaw, leading to expansion of wetlands, after fires (Gibson et al., 2018).

3.3 Climate controls on ENF to DBF transitions

In addition to the impact of disturbance from fire, climate influences the biogeography of changes in ENF and DBF cover that we document in this study. Experimental results have shown that modest increases in temperature can lead to elevated mortality rates in juvenile conifer trees, and that ongoing warming in boreal ecosystems has the potential to cause regeneration failure and replacement of boreal conifers with temperate tree species (Reich et al., 2022). Inspection of the climate envelope of locations where ENF losses and DBF gains are occurring suggest that climate, and by extension climate change, influences where contraction and expansion in ENF and DBF, respectively, are occurring (Figure 4). Specifically, ENF losses are concentrated in the driest regions of boreal North America that are most sensitive to moisture stress from warming temperatures. The bioclimatic distribution of DBF gains, on the other hand, is shifted toward regions that are more mesic and becoming progressively warmer. In this context, less than half of locations where DBF expanded were collocated with disturbance from fire or timber harvest (Table 3). These results suggest that DBF expansion is most prevalent in southern portions of the Canada because they are increasingly favorable to DBF (Reich et al., 2022). Contraction of ENF, on the other hand, is more prevalent in the taiga, where severe fires are common and climate conditions are unfavorable to DBF expansion (see Figure 2).

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Several recent studies have concluded that forest mortality, especially among conifers, is increasing in the southern and western regions of the North American boreal forest (Liu et al., 2023; Peng et al., 2011; Rotbarth et al., 2023; Sánchez-Pinillos et al., 2022). This conclusion, combined with the results we present here showing widespread expansion of DBF, suggests that temperate forests and southern boreal forests in Canada and Alaska are becoming climatically more favorable to temperate DBF species (Brice et al., 2020; Mekonnen et al., 2019; Reich et al., 2022; Soubeyrand et al., 2023). It is worth noting, in this context, that some of the ENF loss that we map in taiga forests may reflect the fact that forest recovery processes are slow in cold regions of the North American boreal forest with short growing seasons. Hence, the 35-year satellite record used for this study may be too short to observe forest recovery in these regions. At the same time, results shown in Fig. 3 demonstrate that in the Alaska Boreal Interior, Plains West, and Shield East ecoregions (all of which include extensive taiga), a large proportion of disturbed ENF have not recovered after 60 years. These results are consistent with field-based studies that document both regeneration failure and shifts from DBF to ENF in Alaska and Canada (. Based on these results, we posit that climate suitability, in combination with ecological adaptation and restructuring arising from climate change and disturbance, explain the biogeography of changes in DBF and ENF that we map in this study.

Figure 3. Land cover change trajectories after disturbance from fire in Canada and Alaska. The pre-fire bar shows the proportional area of different land and forest cover types in the year preceding fire events. Subsequent bars show the proportional area of each land cover and forest type at 10-year time intervals after fire. The first three panels in the top row are ecoregions where the area of ENF decreased and the area of DBF increased after fires. In contrast, the remaining four ecoregions do not show this pattern. The bottom right panel shows results aggregated across all 7 ecoregions.

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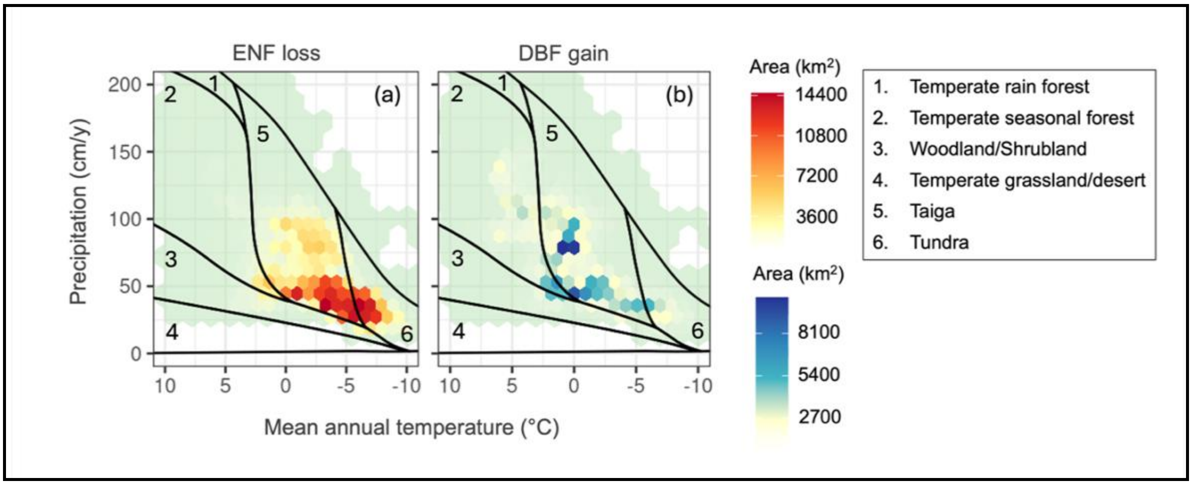

Figure 4. Bioclimatic envelopes showing the location of (a) ENF loss and (b) DBF gain in climate space. Locations where ENF loss and DBF gain occurred with respect to mean annual temperature and precipitation. Black lines show the climate envelopes for major biomes proposed by. The light green area in the background shows the bioclimatic extent of ENF and DBF forests in our study area.

Land Cover Change	Area inside fire perimeters 1985-2020 (km^2)	Area inside fire perimeters 1920-2020 (km^2)	Area of timber harvest locations 1985-2020 (km^2)	Land cover changes co-located with fires or harvest (%)
Evergreen needleleaf forest (ENF) Loss	308,227 (64.0%)	327,269 (68.0%)	56,677 (11.8%)	79.8%
Deciduous broadleaf Forest (DBF) Gain	38,160 (13.6%)	75,523 (27.0%)	48,584 (17.3%)	44.3%
ENF Gain	17,309 (5.8%)	84,356 (28.1%)	4,741 (1.6%)	29.7%
DBF Loss	10,678 (18.8%)	14,162 (24.9%)	14,638 (25.8%)	50.7%
Shrubland Gain	26,952 (17.4%)	35,960 (23.2%)	517 (0.3%)	23.5%

Table 3. Land cover changes inside fire perimeters and timber harvest locations. The area of forest and land cover change for each class inside fire perimeters for 1985-2020 versus 1920-2020 capture recovery processes from fires before 1985. Percentages in parentheses indicate the proportion of each gain or loss category co-located with fires or timber harvest. Note that timber harvest data is not available for Alaska, but timber harvest in Alaska is modest relative to the harvest area in Canada.

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4 Discussion

The time series of land cover and forest cover changes from this study provides compelling evidence that a large-scale shift in the area and PFT composition of forests in Canada and Alaska is underway. Specifically, we show that the area occupied by forests decreased between 1986 and 2020, with concomitant and geographically dependent shifts in the distribution of forest PFTs. The decrease in forest cover that we document largely reflects fire-driven loss of ENF in taiga forests. In the southern boreal and temperate zones, we identify widespread expansion of DBF forests, which we attribute to changes in climate that favor DBF over ENF in these regions.

Increases in fire severity and frequency caused by a warmer and drier climate are the dominant drivers of ENF loss (Johnstone et al., 2016; Mekonnen et al., 2019; Van Nes et al., 2018). However, concurrent changes in post-fire successional pathways and climate that favor establishment of DBF over ENF contribute to this process. In contrast to previous studies that have focused on sub-regions of forests in Canada and Alaska (Hermosilla et al., 2018, 2022; Wang et al., 2020), or that rely on field data (Baltzer et al., 2021; Mack et al., 2021), the results we present in this paper quantify, at high spatial resolution, how the composition of forest cover in Canada and Alaska changed over three and a half decades. In this context, it should be noted that our analysis does not include 2023 and 2024, years with very large areas of disturbance from fire in Canada (Byrne et al., 2024).

Importantly, our remote sensing-based results are consistent with results from field-based studies suggesting that a fundamental shift in the composition and function of temperate and boreal forests in Canada and Alaska may be underway (Baltzer et al., 2021; Mack et al., 2021). Field data provide direct observations of species-level changes at the scale of sparsely distributed locations and are essential for process and species-level understanding of ongoing changes. However, extrapolation of results from these studies over the very large and remote areas occupied by forests in Canada and Alaska is difficult. Using remotely sensed information that has been carefully calibrated to forest inventory data and rigorously assessed via independent reference data, our analysis provides a quantification of the area, location, and timing of changes at continental scale that complements and supports results from field-based studies. In addition, multitemporal information available from time series of Landsat imagery enable changes in successional pathways to be identified across ecoregions in a manner that is difficult from field-based studies (cf. Figure 3).

The integrity of the results we present depends on the quality and defensibility of our map-based analysis. In this context, the rigor and quality of error and bias quantification in our forest cover change estimates provide confidence that our results are robust and defensible (Olofsson et al., 2014). This last point is critical because recent remote sensing-based papers have drawn substantially different conclusions regarding the nature and magnitude of changes in ENF and DBF in Canadian and Alaskan forests (Hermosilla et al., 2024, 2025; Massey et al., 2023; Potapov et al., 2008; Wang et al., 2020). The Supplementary Information included with this paper provides additional details that describe the accuracy assessment we performed for this work, and discusses the nature and sources of disagreement between results from this study versus other

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remote sensing-based studies. In particular, we discuss challenges involved in assessing and quantifying uncertainty in estimates of land cover change over large areas, emphasizing differences in the character of accuracy assessments that have been performed across these studies and providing confidence that the results we present in this paper are robust.

The changes that we identify have important implications for large-scale biosphere-atmosphere interactions, and by extension, the high-latitude climate system. Deciduous trees grow faster, are more productive, and have higher rates of respiration than conifer tree species (Goulden et al., 2011; Mack et al., 2021). Hence, contraction of ENF and expansion of DBF has the potential to alter large-scale carbon budgets by increasing rates of photosynthesis and decomposition, increasing the seasonal amplitude of atmospheric CO_2, and shifting carbon stocks from belowground to aboveground pools (Goulden et al., 2011; Kim et al., 2024; Mack et al., 2021; Zimov et al., 1999). Similarly, deciduous forests have higher albedos and latent heat fluxes than conifer forests, providing a net cooling effect relative to evergreen forests (Randerson et al., 2006; Rogers et al., 2013). Over the very large area occupied by forested ecosystems in Canada and Alaska, these land surface changes have the potential to fundamentally change the central role of boreal ecosystems in the global climate system (Chapin III et al., 2000). Given the current rate of warming in boreal regions, which was the key driver leading to extreme fire years in both 2023 and 2024 (Byrne et al., 2024), the changes we identify are likely to continue, and may accelerate, in the coming decades. Most current climate models do not realistically represent or capture the role of disturbance in boreal carbon budgets (Wang et al., 2021), nor do they account for the ongoing changes in successional and other ecological processes (Baltzer et al., 2021; Reich et al., 2022) that we document in this study. Hence, as the boreal climate continues to warm and disturbance regimes continue to intensify, sustained monitoring will be required to document further changes in the structure, composition, and function of temperate and boreal forests, and to improve understanding and models of how these changes propagate into the climate system.

5 Conclusions

We used 35 years of Landsat-derived land cover maps calibrated and validated against extensive forest inventory and reference data to identify large-scale, systematic shifts in forest composition and land cover across boreal and temperate ecoregions of Canada and Alaska. Between 1986 and 2020, nearly 11% of the forested landscape experienced land cover change. Evergreen needleleaf forest decreased in fire-prone taiga regions, while deciduous broadleaf forest and shrublands expanded in warmer, moister areas in the southern Canada and Alaska. Ecoregion-specific patterns of post-fire succession indicate that these changes reflect the impact of increasingly frequent and severe wildfires and a shift in successional trajectories following disturbance, with several ecoregions failing to recover their pre-fire levels of evergreen needleleaf forest cover six decades after fire. The bioclimatic conditions where evergreen needle forest loss and deciduous broadleaf forest gain occurred suggest that climate change is reshaping not only where disturbance occurs, but how forests recover from it.

Because a systematic shift from evergreen to deciduous forests alters surface albedo, latent heat exchange, and the balance between photosynthetic carbon uptake and disturbance-driven carbon release, the land cover changes that we report have direct implications for the role of boreal and temperate forests in the climate system. Current land-surface and carbon-cycle models generally do not resolve or represent the disturbance-mediated successional changes that we document. Hence, the systematic shifts in land cover documented here (and the feedbacks they induce) are likely absent from projections of high-latitude climate change. Given that warming and fire activity in boreal and temperate regions continue to intensify — as illustrated by the record-breaking 2023 and 2024 fire seasons — the land cover changes that we identify are likely to persist and may even accelerate in the coming decades, underscoring the need for sustained satellite monitoring and improved representation of disturbance and succession in Earth system models.

Data availability

Map results from this work are publicly available via NASA's Oak Ridge National Laboratory Distributed Active Archive Center:

Hu, K.T., J.A. Wang, X. Zhu, W. Liang, D.C. Morton, J. Kim, J.T. Randerson, and M.A. Friedl. 2025. ABoVE: Landsat-derived Annual Boreal Dominant Land Cover, 1986-2020. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/2423

All remote sensing and training data used for this work, including the Canadian Forest Service NFI data are openly available to the public.

Supplement link

The link to the supplement will be included by Copernicus.

Author contributions

Conceptualization: KTH, MAF, JAW and JTR
Methodology: KTH, MAF, JW
Investigation: KTH, MAF, JAW, XZ
Funding Acquisition: MAF, JAW, JTR
Project administration: JAW, MAF, JTR
Supervision: MAF
Writing – original draft: KTH and MAF
Writing – review & editing: JAW, XZ, WL, DCM, JEK, JTR, MAF

Competing interests

Authors declare that they have no competing interests.

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