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The boreal biome is Earth's most expansive, ecologically intact, and climatologically sensitive forest. The boreal forest comprises a third of the global forest area and accounts for 20.8% of the total forest carbon (C) sink¹. The boreal region contains 38 ± 3.1 Pg C of above-ground biomass² and is underlain by 1672 Pg C, summing to total biomass rivaling the tropics and half of global soil C—of which 88% is locked in permafrost^{3,4}. Boreal vegetation structure also controls the reflective and thermal balance of solar radiation of the high northern latitudes via canopy albedo, posing a positive feedback mechanism for greenhouse atmospheric warming^{5–8}.

The boreal region has experienced the fastest climatological warming of any forest biome, with annual surface temperatures increasing $> 1.4^\circ$ C over the past century⁹. Boreal forest dynamics are highly correlated to climate^{10–12}, and increases in vegetation productivity have been observed across the northern high latitudes¹³. Meanwhile, regional increases in the frequency and severity of windthrow, fire, insect, and disease events have been reported as well³.

While theory predicts a northward shift of the boreal forest, the net effect of the many opposing factors on the region's tree canopy remains an untested hypothesis. Coupled climate-vegetation models predict a net-northward migration of boreal vegetation due to warming^{14,15}, supporting the dominance of growth processes, and multiple studies^{16–18} have reported vegetation “greening” based on general indices of plant productivity. However, the slow productivity of boreal tree cover requires long-term analyses, which have been either confined to regional scopes or poorly calibrated data^{19–21}. As a result, the net effect of growth and mortality on the

distribution of the boreal tree canopy, and the resulting effect on carbon budgets, remain unconfirmed.

Here we report the results of a global test of the magnitude and direction of boreal-forest change from 1984 to 2020, as observed through historical satellite records of tree cover. We calibrated machine learning algorithms^{22,23} to 224,026 Landsat images covering the boreal forest and adjacent tundra on the Amazon Web Services (AWS) cloud-computing architecture to estimate tree-canopy cover over space and time. The resulting 30-meter, annual-resolution dataset—the most extensive and highest-resolution record of boreal tree cover to date—was then subjected to time-series trend analysis to estimate and map the historical direction, rate, and significance of change across the region.

Distribution of boreal tree-canopy cover

The tree canopy is densest in the southern portions of the biome and thins with increasing latitude (Fig. 1)²³. Sparse conifer forest, woodland, herbaceous, and non-vegetated cover increase in frequency into and across the taiga-tundra ecotone, and tree cover is nearly absent above 71°N. Including unforested tundra, wetlands, and inland water bodies, the most common range of tree cover is below 5%.

The boreal forest increased in density from 1985 to 2020 (Fig. 2). Trees covered 7.153 million km² (41.44 %) of the region in 1985 and 7.997 million km² (46.32 %) in 2020, increasing linearly 0.023 million km²/yr (0.12%/yr) over the 36-year period (percent cover = $0.116 \times \text{year} - 187.6$, $R^2 = 0.79$, $p < 0.001$). Given the 10-30% range of tree-canopy cover defining forests within the United Nations Framework Convention on Climate Change²², the region held

45 between 8.95 to 12.41 million km² of forest in 2000 and increased to between 9.41 and 13.26
46 million km² of forest in 2020.

47 The boreal forest also shifted northward from 1985 to 2020. The mean latitude of boreal tree-
48 canopy cover increased half a degree, from 57.37 °N to 57.66 °N over the period (mean latitude
49 = $0.0075 \times \text{year} + 42.6$, $R^2=0.79$, $p < 0.001$). Median latitude increased at a faster rate than the
50 mean (median latitude = $0.0124 \times \text{year} + 32.5$, $R^2 = 0.88$, $p < 0.001$), implying widespread
51 growth across the entire biome rather than changes at either its outlying northern or southern
52 margins.

53

Fig. 1 | Current (2020) distribution of tree-canopy cover across boreal and arctic tundra ecoregions. The tree-canopy cover was estimated at 30-meter pixel resolution by machine learning algorithms applied to all available Landsat satellite images from the year 2020; data gaps due to clouds were filled with estimates from earlier years. Ecoregions were defined by ²⁴. The bottom panel shows northward migration of the distribution of boreal tree-canopy cover from 1984 to 2020.

The pace and pattern of boreal forest change

These global totals comprise the balance of strong geographic variation (Fig. 2). Net canopy gains occurred at every latitude above 53°N from 1984 to 2020, with the strongest increases occurring between 64 to 68°N. While not seeking a distinct line *per se*, net gains in the region's highest latitudes support the hypothesis of a positive shift in the northern limit of tree cover, or “northern tree line”. In contrast, net canopy losses were smaller in magnitude and confined to the lower boreal latitudes (45-51°N), where human activity is most intense (Fig. 3).

In North America, significant net gains were concentrated in the northernmost portion of the domain, where increases in shrub and grass cover have also been reported ²⁵. Regions of significant net losses corresponded to areas of widespread forest disturbance, including fire and bark beetle (*Dendroctonus spp.*) outbreaks in British Columbia ²⁶, spruce budworm (*Choristonura sp.*) outbreaks in Quebec ²⁷, and fires across the central Canadian provinces and interior Alaska ²⁸.

In Eurasia, hotspots of forest loss included the eastern Russian-Chinese border and agricultural regions of the southern boreal margin east of the Ural Mountains, as well as areas of forest felling near the Russia-Finland border in the 1990s ²⁹ and increased fire frequency and intense selective logging ³⁰. Net losses were notably rare in Europe ³¹. Corroborating reports of increasing coverage of tall shrubs and larch (*Larix spp.*) in the Siberian ecotone ³², regions of significant net gain included areas of post-Soviet agricultural abandonment and reforestation, as well as larch forests underlain by permafrost in the Yakutsk region of eastern Siberia. In these forests, permafrost thawing has been hypothesized to result in increased forest productivity ³³, and vegetation recovery from wildfires in the 1990s is ongoing ³⁴.

Fig. 2 | Spatial and temporal distribution of boreal tree-canopy cover change from 1984 to 2020. Map: Significant net gains (green-blue) and losses (orange-red) of tree-canopy cover over the boreal biome. Table (top-right): Linear regression slope of tree canopy-cover over time, stratified by latitude. Bottom panel: northward migration of the distribution of mean and median latitude of tree-canopy cover. All image tiles included in the analysis had >30 unobscured observations from 1984 to 2020.

83 The pan-boreal increase in tree cover occurred against a backdrop of relatively stable rates of
 84 disturbance over the period (Fig. 3). The region-wide rate of disturbance accelerated from 53,546
 85 km²/yr in 2000 to 60,275 km²/yr in 2020— equating to an increase of 1.8%/yr (1,100 km²/yr)
 86 ($y=1,099.57x - 2,157,378.02$, $R^2=0.27$, $p\text{-value} = 0.016$) or 0.2 to 0.4% of the maximum forested
 87 area of the region over the period. In contrast to net gains, the latitudinal distribution of
 88 disturbances fluctuated from year to year while remaining stationary over the period as a whole
 89 ($y=0.04x - 25.16$, $R^2=0.14$, $p\text{-value}: 0.023$).

90 Previous studies have sought evidence of a northward shift of the boreal biome at the northern
 91 limit of tree cover. While reports of advances in the northern tree line based on globally
 92 calibrated datasets have been contested for coarse categorization of the forest and poor
 93 calibration ^{35,36}, our observations based on regionally calibrated estimates corroborate the
 94 advancement hypothesis, as well as independent reports of disturbance and recovery ^{16,37–40} and
 95 in situ measurements of changing woody structure near the northern limits of tree growth ^{32,41}.
 96 Whereas we sought neither evidence of a discrete northern edge to the boreal forest or changes
 97 therein, our results do show a biome-wide northward shift in the entire distribution of tree
 98 cover—including the gradient spanning its northern extreme.

Fig. 3 | Total area and median latitude of boreal stand-clearing disturbances from 1985 to 2020.

Distribution of boreal forest age

We also retrieved the spatial and frequency distribution of current forest stand age across the boreal biome. While most of the boreal forest area (8.19 million km², 47.5% of the region) is older than what can be measured from the 37-year satellite record (Fig. 4), some observations of the region's youngest forests can be made empirically. In 2020, 0.5 million km² (or 5.29% of standing forests) were those that had been identified as forest in 1984, disturbed at some time during the period, and recovered again to forest by 2020. The total of these recovering forests and expanding "new" forests within the observable period have led to a weak mode of young stands between 9 and 21 years of age, as well as a current lapse in the youngest age classes. These young forests are especially prevalent in areas of intensive forestries, such as the industrial plantations of Scandinavia, as well as areas recovering from wildfire. The latter is corroborated by reports of increasing frequency and area of burns in Siberia since the end of the 20th century⁴², the demographic effect of which is reflected in an increasing proportion of recovering forest < 20 years old.

Fig. 4 | The distribution of stand age (top) across the boreal ecoregion, and frequency distribution of boreal stand age in 2020 (bottom). Forest age-class distribution is defined as years since the establishment of pixels that were forested in 2020.

The carbon impact of young forests

The impact of the young forests on the boreal carbon budget is significant, and it could explain the region's increasing carbon sink ⁴³. Forests with known stand ages (≤ 36 years since disturbance) hold between 1.1 – 5.9 Pg C, based on recent models ⁴⁴. Ages of forests where no disturbance was recorded during the observation period are unknown, yet plausible carbon-stock values within the oldest forested age class may be bracketed between a lower, younger limit (19.1 – 58.4 Pg C) and an upper, older limit (300 years stand age, 42.4 – 89.2 Pg C). Based on these estimates, all forested area of ages ≤ 36 years comprises 1.35% to 14.20% of the total carbon stock in aboveground biomass in the boreal forest, which increases with the fractional area of young (≤ 36 -year) forest to total forest area (15.4%). Allowing all these young forests to mature without disturbance would result in a potential additional carbon sink of 2.3 – 3.8 Pg C.

The amount of carbon in forests new to the satellite record is 0.8 – 3.5 Pg C, greater than carbon in forests recovering from observed disturbances (0.3 – 2.4 Pg C). Over the next 36 years, these “new” forests represent a potential additional carbon sink of 1.3 – 2.0 Pg C (0.036 - 0.18 Pg C/yr), compared to 1.0 – 1.8 Pg C (0.028 - 0.05 Pg C/yr) in recovering forest. The differences in present-day stocks and the carbon sink potential between new and regrowing forests can be partly explained by the greater area of new forests compared to regrowing forests (7.6% and 6.7% of total forest area, respectively), but also by the greater age of new forests compared to those forests recovering from disturbances within the record.

The amount of carbon sequestered by the new forests could be large enough to offset the effect of warming on boreal ecosystem respiration, estimates of which vary from 5 Pg C to 28 Pg C from 1985 to 2020 (SI). Climate warming and CO₂ fertilization are expected to increase productivity in these regions ⁴⁵; and interestingly, the observed spatial pattern of net canopy

growth confirms model predictions of enhanced seasonal CO₂ exchange at latitudes > 40°N¹³. However, several factors could yet reduce the offset of forest expansion on a temperature-mediated increase in respiratory fluxes, including: the temperature effect itself can be temperature dependent⁴⁶, sink capacity eventually decreases with age⁴⁷, thawing of carbon locked in permafrost will accelerate respiration⁴⁸, and changes in fire regimes and wood harvest could overshadow stocking from forest development^{3,42}. It also remains unclear to what extent the expansion of trees, with longer lived carbon pools than herbaceous vegetation, can be structurally sustained by boreal soils⁴⁹, or on how disturbed area might increase from human activity. Each of these dynamics is already taking place across the boreal domain, and strategies to quantify the potential tradeoffs between autotrophic and heterotrophic dynamics are key to understanding the role of forest management in mitigating the causes and consequences of climate change in the boreal domain.

Conclusions

A pan-boreal test of the magnitude, direction, and significance of boreal forest change has confirmed the climatological and ecological hypothesis of northward migration of the boreal biome. Machine learning was used to retrieve the longest, highest resolution, and most complete calibrated record of boreal-forest change from the historical satellite record to date. Time-series analysis of each of the 1.9×10^8 30-m pixels over 37 years revealed increasing canopy density and northward migration of the boreal forest from 1984 to 2020 despite relatively even rates of forest disturbance over the period. Recent models of the relation of forest age to biomass stocks and change suggest the changing distribution of age will significantly affect the region's contribution to the global carbon budget in coming decades.

While globally significant, the trends belie tremendous variation over space and time, as well as in the processes underlying the observable changes. A deeper understanding of the full complexity of the causes and consequences of canopy changes across the boreal forest will require analysis against coincident measurements of canopy structure and the environmental determinants of growth and mortality. Further, translating the resulting information into action to forestall and adapt to climate change will require effective communication across scientific, government, and commercial domains.

Online content

The current distribution of boreal tree canopy cover and its changes over time can be explored publicly at <https://www.terraPulse.com/terraView/ccs>.

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Figures

Figure 1

Current (2020) distribution of tree-canopy cover across boreal and arctic tundra ecoregions. The tree-canopy cover was estimated at 30-meter pixel resolution by machine learning algorithms applied to all available Landsat satellite images from the year 2020; data gaps due to clouds were filled with estimates

from earlier years. Ecoregions were defined by 24. The bottom panel shows northward migration of the distribution of boreal tree-canopy cover from 1984 to 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Spatial and temporal distribution of boreal tree-canopy cover change from 1984 to 2020. Map: Significant net gains (green-blue) and losses (orange-red) of tree-canopy cover over the boreal biome. Table (top-right): Linear regression slope of tree canopy-cover over time, stratified by latitude. Bottom panel: northward migration of the distribution of mean and median latitude of tree-canopy cover. All image tiles included in the analysis had >30 unobscured observations from 1984 to 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Total area and median latitude of boreal stand-clearing disturbances from 1985 to 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

The distribution of stand age (top) across the boreal ecoregion, and frequency distribution of boreal stand age in 2020 (bottom). Forest age-class distribution is defined as years since the establishment of pixels that were forested in 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square

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