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High-carbon primary forests as conservation targets in Ontario, Canada

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Ontario's forests are changing rapidly under the pressure of industrial logging, coupled with the effects of climate change, which is facilitating increased wildfires. The reduction of mature and old-growth forests negatively affects ecosystem functions, including wildlife habitat suitability and long-term carbon storage. Here, we present an operational mapping tool to identify and monitor the extent of high-carbon primary forests (HCPF) to support their protection and track progress toward the Kunming-Montréal Global Biodiversity Framework's Target 3. We define HCPF as mature and old-growth, naturally regenerated forests that have not experienced tree canopy disturbance over the past 50 years and are located within unfragmented landscape patches with a minimum area of 1,000 ha. By integrating existing maps, satellite-based products, and detailed manual image interpretation, we mapped 28.4 Mha of HCPF in Ontario for 2020. HCPF comprised 80.7% of all forests outside industrial timber concessions, whereas within private and industrial forests, their percentage was much lower (29.7%). They represented less than 2% of all forests within the Mixedwood Plains ecozone of southern Ontario. The HCPF vegetation carbon stock density is higher than that of fragmented and recently disturbed forests by 7% within the entire province, and by 18% within the region of industrial forestry. Ontario's unfragmented landscapes contain more than 72% of the total soil organic carbon stock of the province, illustrating their importance for long-term carbon storage. Unfragmented landscapes are essential for the survival of Ontario's woodland caribou populations; however, their percentage within most caribou population ranges was below the management threshold of 65% and continued to decline. From 2021 to 2025, Ontario's HCPF area decreased by 3.5% (0.2 Mha/yr) due to wildfires and logging. Within the region of industrial forestry, the proportion of 2021–2025 logging within HCPF exceeded that in non-HCPF forests, and the annual logging area within HCPF increased by 55%. This acceleration of logging and associated road construction illustrates that HCPF, as opposed to secondary forests, continue to be the major source of timber in Ontario. The HCPF method provides the tools and data required to accurately assess and monitor mature and old-growth primary forests, and to develop effective conservation strategies and policies at the provincial and national levels. As demonstrated for Ontario, the HCPF method can be applied to all provinces to facilitate the protection of some of the last remaining primary forests in Canada.

KEYWORDS
forest conservation, Landsat, landscape fragmentation, old-growth forest, primary forest

1 Introduction

Human activities over the past millennia have transformed North American temperate and boreal forest ecosystems (Peacock, 1998; Christianson et al., 2022). Forest distribution, composition, structure, and dynamics in Canada are shaped by historical and current anthropogenic pressures, ranging from traditional practices to land use conversion and climate change (Flannigan and Wagner, 1991; Stewart, 2002; Johnson and Miyanishi, 2012; Abrams and Nowacki, 2015; Jones et al., 2022). The past two centuries of industrial development, coupled with increased fire frequency and severity due to climate change, have accelerated the transformation of forest ecosystems. This has resulted in the loss of mature and old-growth forests (Mosseler et al., 2003; Cyr et al., 2009; Henry and Quinby, 2021; Price et al., 2021; Quinby, 2025), changes in species composition beyond the natural range (Bouchard and Pothier, 2011; Bergeron et al., 2017; Grondin et al., 2018; Martin et al., 2021), reduction of woodland caribou habitat (Joly et al., 2012), decline in forest carbon storage capacity and an increase in CO_2 emissions (McDowell et al., 2020; Byrne et al., 2024), and health impacts on human populations due to smoke pollution from wildfires (Flood et al., 2025).

Despite a long history of resource exploitation, some of Ontario's forest landscapes remain minimally affected by development (Quinby, 1991; Potapov et al., 2017; Quinby et al., 2022; Mackey et al., 2024). However, the area of undisturbed landscapes is shrinking due to road construction, resource extraction, and increasing wildfire frequency (Potapov et al., 2017, 2025; Grondin et al., 2018; Mackey et al., 2024). Protecting forests that remain minimally impacted by industrial development and fragmentation is crucial for preserving species habitats, maintaining ecosystem functions and services, and supporting the livelihoods of Indigenous communities (Mackey et al., 2015). Canada and Ontario have adopted the Kunming-Montréal Global Biodiversity Framework (ECCC, 2024), which calls for a protection target of at least 30% of natural terrestrial ecosystems, prioritizing areas important for biodiversity and ecosystem functions and services. Expanding forest protection areas is especially relevant for Ontario, where a proposed doubling of industrial logging (Quinby et al., 2022; Quinby, 2025), coupled with increasing annual burn area (Byrne et al., 2024), threatens the integrity of remaining primary forests.

Several approaches for identifying forest conservation targets are relevant to Ontario. Primary forests are considered a principal target for protection given their importance for biodiversity, climate change mitigation through carbon sequestration, water cycle regulation, spiritual and cultural values, and other ecosystem functions and services (Mackey et al., 2015; Kormos et al., 2018). The Food and Agriculture Organization of the United Nations (FAO, 2023) defines primary forest as "naturally regenerating forest of native tree species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed". According to this definition, primary forests may include areas affected by traditional forest management by Indigenous communities and other historical human uses, provided that the structure and function of the forest ecosystem have been restored. However, the FAO definition does not account for forest age and may include young forest stands recovering after natural disturbances. Although the FAO definition implies that individual primary forest patches should be large enough to maintain ecosystem integrity, it does not specify quantitative criteria for fragmentation assessment, such as minimum forest patch size.

Satellite-based approaches for primary forest mapping consider only mature natural tree canopy cover that has not been completely cleared and regrown in recent history (Turubanova et al., 2018). A similar approach was implemented by Mackey et al. (2024), who mapped undisturbed mature and old-growth forests within the southern boreal forest of Ontario using the integration of Forest Resources Inventory data and Landsat-based disturbance maps. However, neither approach accounts for landscape fragmentation or the long history of forest disturbances.

The "old-growth forests" concept is another well-established forest conservation prioritization tool directly linked to the primary forest concept (Quinby, 1991; OMNR, 2003a, 2003b; Henry and Quinby, 2021; Quinby, 2025). Old-growth forests represent a component of the primary forests defined through the presence of old trees and deadwood, as well as through their structural complexity and integrity (OMNR, 2003b; Hilbert and Wiensczyk, 2007; Quinby and Marcus, 2026). In Ontario, their practical definition is based primarily on stand age criteria (the age-of-onset) (OMNR, 2003b), which for most tree species is greater than 100 years. Old-growth forests are irreplaceable for supporting populations of late-successional species and providing a baseline for forest restoration (Frelich and Reich, 2003). Sustainable forest management initiatives acknowledge old-growth forests as indicators of ecosystem health in Ontario (OMNR, 2003a), however, the Governments of Canada and Ontario have not yet provided standards and protocols for assessing key features of old-growth forests, such as old tree density and biomass, deadwood (snags and logs) density and biomass, and cut stump density, which indicate ecological integrity (Quinby and Marcus, 2026). Currently, empirical field data are required to verify the presence of old-growth forests (Quinby and Marcus, 2026). However, obtaining field data substantially increases the costs and limits the geographic scope of such assessments.

In contrast to the old-growth forests assessment, landscape fragmentation analysis prioritizes forests for conservation by focusing on large, unfragmented areas with limited human access (Ibisch et al., 2016; Potapov et al., 2017; Poley et al., 2022; Quinby et al., 2022). These areas are characterized by high resilience to natural disturbance and climate change, and they generally support viable populations of wide-ranging mammal and bird species (Potapov et al., 2008). The roadless areas (RA) dataset produced by Quinby et al. (2022) combined detailed provincial infrastructure maps with industrial logging data derived from Ontario's Forest Resource Inventory spatial database. The limitations of the publicly available infrastructure (Poley et al., 2022) and the use of outdated logging maps (Pinto et al., 2007; Thompson et al., 2007) caused the underestimation of forest fragmentation by the RA approach. The Intact Forest Landscapes (IFL; Potapov et al., 2017) mapping approach is a simple yet labor-intensive method that maximizes forest fragmentation mapping accuracy by integrating available maps, satellite-based products, and visual interpretation of satellite time series. The IFL assessment uses the minimum unfragmented patch area of 50,000 ha, which is necessary to operationalize mapping at the global scale. However, since IFL are mostly found outside of the commercial timber concessions and private lands in Ontario, this approach does not facilitate the identification of conservation targets within the southern part of the province, where only small patches of unfragmented landscapes remain.

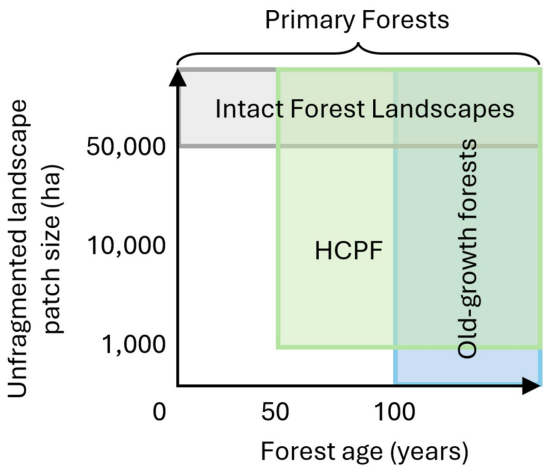


FIGURE 1
The relationship between the forest conservation target definitions. The entire plot area represents primary forests, as defined by FAO (2023). Intact Forest Landscapes (Potapov et al., 2017) and old-growth forests (OMNR, 2003b) represent sub-categories of primary forests defined by either forest fragmentation or forest age criteria. The proposed high-carbon primary forests (HCPF) definition integrates fragmentation and stand age criteria (see Section 2.1). The remaining primary forests represent (i) young forest stands recovering after natural disturbances and (ii) small fragments of mature primary forests within a developed landscape.

The old-growth forests, RA, and IFL definitions all exclude tree plantations and industrially logged forests and thus represent sub-categories of primary forests providing complementary approaches for conservation targeting (Figure 1). Old-growth forests represent a sub-category of primary forests defined by forest age that excludes young forest stands originating after natural disturbances. The IFL represent large landscape-level primary forest fragments that may contain forest stands of different ages. Both approaches, however, exclude smaller (less than 50,000 ha) fragments of mature forests younger than 100 years of age, which prevents the identification of forest conservation targets within historically managed areas of Ontario.

Here, we present a novel approach to map and monitor forest conservation targets across the entire province of Ontario based on the history of forest disturbances and landscape fragmentation criteria that can be directly measured using publicly available maps and satellite imagery. Our high-carbon primary forests (HCPF) definition integrates the values of mature and old-growth forests with the concepts of roadless areas and intact landscapes by selecting primary forests at least 50 years old within unfragmented landscapes of at least 1,000 ha in size. As a sub-category of primary forests, HCPF definition accounts for anthropogenic landscape fragmentation, a proxy of ecosystem integrity and resilience, and facilitates prioritization of mature and old-growth forests that are important for biodiversity support and climate change mitigation (Figure 1). Our approach improves the RA assessment methodology (Quinby et al., 2022) by accounting for pre-1985 forest disturbances and improves the IFL approach (Potapov et al., 2017) by including smaller fragments of mature forest within largely developed landscapes. The resulting 2020 HCPF map and 2021–2025 monitoring results[1] provide support for forest management and conservation planning to protect Ontario's most valuable and vulnerable primary forests.

2 Methods

2.1 HCPF definition and criteria

We define high-carbon primary forests (HCPF) as mature and old-growth, naturally regenerated forests not affected by tree canopy loss over the past 50 years, located within unfragmented landscape patches with an area of at least 1,000 ha. This definition integrates ecological significance with practical constraints imposed by publicly available spatial datasets and satellite data archives, balancing conservation priorities with methodological feasibility at the provincial scale. We chose the term "high-carbon" to highlight that HCPF represent the portion of primary forests with the highest carbon stock density, which we confirmed by our analysis (Section 3.4). The HCPF do not represent solely "pristine" primary forests never affected by human activities. They also include mature naturally regenerated forests that are rare within the most developed southern part of the province and thus represent high conservation value ecosystems. The HCPF definition is based on two groups of criteria described below.

2.1.1 Forest age criteria

HCPF comprise mature and old-growth forests with no evidence of canopy loss since the 1970s, resulting in a minimum forest age of approximately 50 years. This age criterion was applied without regard to the proximate causes of tree cover loss events, thereby excluding young forests regenerating both after logging and after natural disturbances such as wildfires.

No digital spatial data enabling reliable historical (1970–2020) disturbance mapping at high spatial resolution are available for Ontario. Therefore, we used the 30-m spatial resolution Landsat data archive to detect recent (1985–2020) forest disturbances and young forests regenerating after tree cover loss events that occurred as early as 1970. Since forest disturbances before the 1970s could not be reliably identified using the 30-m Landsat data archive, a minimum age of 50 years was chosen for both practical and ecological reasons. Forests that regenerated naturally after pre-1970 disturbances, including logging, were classified as HCPF if they met the landscape fragmentation criteria.

The proximate causes of historical disturbances cannot be consistently determined using satellite data for temperate forests of Ontario, where logging and wildfires interact and overlap. In addition, it is impossible to separate lightning-caused fires from human-ignited fires using remotely sensed data. While wildfire is a natural component of boreal forest dynamics, fire frequency and extent are increasing in Canada due to human-caused climate change (Flannigan and Wagner, 1991; Oris et al., 2014; Seidl et al., 2020; Byrne et al., 2024). Together, industrial logging and wildfires reduce the extent of mature and old-growth forests and cause habitat loss for native species, such as woodland caribou (Palm et al., 2022). These considerations justify excluding young forests that originated after all types of forest disturbances.

1 https://zenodo.org/records/18565690

2.1.2 Landscape fragmentation criteria

Our fragmentation assessment is built upon the Intact Forest Landscapes (IFL; Potapov et al., 2017) and roadless areas (RA; Quinby et al., 2022) methodologies, which were modified for application at the provincial level. Ontario forests are naturally fragmented by non-forest ecosystems, such as wetlands, rock outcrops, lakes, and rivers. Natural fragmentation was not accounted for in the HCPF mapping. Only tree cover loss events and anthropogenic features were considered as fragmentation elements. In addition, we applied a 100 m buffer zone along long-lasting anthropogenic forest edges, specifically, along transportation infrastructure, mining sites, built-up areas, and agricultural lands. Buffer zone width was selected based on the estimated distance of anthropogenic edge influence on forest ecosystems (Harper et al., 2005), which averaged 100 m for the most sensitive edge metric of "individual species abundance" (Franklin et al., 2021). We acknowledge that woodland caribou in Ontario's boreal forest can be affected by noise from logging activity up to 13 km away (Vors et al., 2007); however, using a 13-km buffer zone was not practical for this study. Field studies are needed to better understand edge effects on Ontario's forest biodiversity, particularly given the widespread and significant impacts of roads in the province (Quinby et al., 2022; Quinby, 2026).

There is no consensus on minimum patch size or corridor width for mapping unfragmented landscapes. Suggested minimal patch sizes for Canada range from 200 ha required to support edge-intolerant and area-sensitive forest species (Environment Canada, 2013) to 50,000 ha used for the IFL mapping (Potapov et al., 2017). We used a minimum patch size of 1,000 ha since it represents an ecologically viable threshold (World Bank, 2026) below which smaller forest patches are generally incapable of self-replacement (Quinby, 1991). The selected minimal patch size is 5-10 times smaller than the recommended minimal protected area size in ecosystems with large-scale disturbance dynamics, such as wildfires and insect outbreaks (Pickett and Thompson, 1978; Edwards et al., 2022). However, such large minimal patch size would limit the practical application of our approach in southern part of the province where most forest landscapes are historically transformed and fragmented. By providing consistent province-wide data on the remaining unfragmented patches with a minimum size of 1,000 ha we allow implementation of landscape-specific thresholds for their conservation prioritization within each management area.

In addition to the minimum patch size, we also used a minimum corridor and appendage width of 100 m to provide for effective species movement within the selected unfragmented patches (Environment Canada, 2013; Franklin et al., 2021). We acknowledge that this width does not apply to large mammals (Bentrup and Shi, 2025) since they are generally able to travel through young forest (<50 yrs.) or the human matrix to reach suitable habitat.

2.2 Mapping methodology

The HCPF mapping workflow included two main steps: landscape fragmentation assessment to select unfragmented landscapes for the year 2020, and land cover attribution of selected unfragmented landscapes to map HCPF (Figure 2). We mapped unfragmented landscapes and HCPF within the Province of Ontario, Canada, for the year 2020. The province's extent was obtained from the 2021 Census boundaries (Statistics Canada, 2024a). The fragmentation analysis was performed within the provincial area plus a 50 km buffer around the provincial boundary to include unfragmented patches shared with neighboring provinces; the final map was clipped to the provincial boundaries. Our study area excluded open water more than 500 m away from the closest land (Figure 3A) based on the 2020 Landsat-based permanent water map (Potapov et al., 2022a).

2.2.1 Landscape fragmentation assessment

The fragmentation analysis included the identification and mapping of forest disturbances and anthropogenic features that are considered fragmenting features. These include 1970–2020 forest disturbances caused by either natural factors such as fire, wind, flood, insects, and diseases, or mechanical tree removal from timber harvesting or land use conversion, resulting in treeless areas or forest stands younger than 50 years old as of 2020. In addition to forest disturbances, the following anthropogenic features were considered as fragmenting features: all roads (including logging, industrial access, abandoned, and winter roads), railroads, power lines, pipelines, and mineral resources exploration and extraction infrastructure (quarries, wells, and seismic lines). Converted and intensively managed lands, such as built-up lands comprising settlements and industrial sites, and agricultural lands comprising croplands and managed pastures, were also considered fragmenting features and were excluded. Natural water bodies were not considered fragmenting features except for water reservoirs, lakes, and rivers used for transportation or recreation. We considered the adjacency of water bodies to human infrastructure as evidence of man-made reservoirs and/or water transportation routes.

We obtained forest disturbance extent, converted lands, and anthropogenic features from existing national and provincial maps, and mapped forest disturbances and young forest stands using the Landsat data archive. Most of the roads and other linear infrastructure (pipelines, power lines) were extracted from publicly available digital maps produced in 2019-2021, including Open Street Map (OSM, 2024); the National Road Network (Statistics Canada, 2024b), the Ontario Road Network and the MNRF Road Segments (Ontario Ministry of Natural Resources (OMNR), 2024a,b); and utility lines dataset (Ontario Ministry of Natural Resources (OMNR), 2024c). Converted and managed lands, such as settlements, cropland, and managed pastures, were extracted from the 2020 AAFC Land Use dataset (Agriculture and Agri-Food Canada, 2024), WorldCover 2021 (Zanaga et al., 2022), and the global cropland extent dataset for 2019 (Potapov et al., 2022b). The year 2020 permanent water layer from the Landsat-based land cover and land use dataset (Potapov et al., 2022a) was used to select water bodies with an area of at least 100 ha that included any portion of the 100-m buffer zone along linear transportation infrastructure and built-up lands. We consider such water bodies as fragmenting features.

Forest dynamics datasets provided by the National Forest Information System (NFIS) served as the primary data source for mapping forest disturbances and stand age. Burned and industrially logged areas between 1985 and 2020 (Hermosilla et al., 2016) were used as indicators of young and regrowing forests, and forests 30 years and younger were identified from the 2019 forest age database (Maltman et al., 2023). Young forests up to 30 years old were also extracted from the 2020 AAFC Land Use dataset (Agriculture and Agri-Food Canada, 2024). Burned forest areas from 1972 to 2020 were

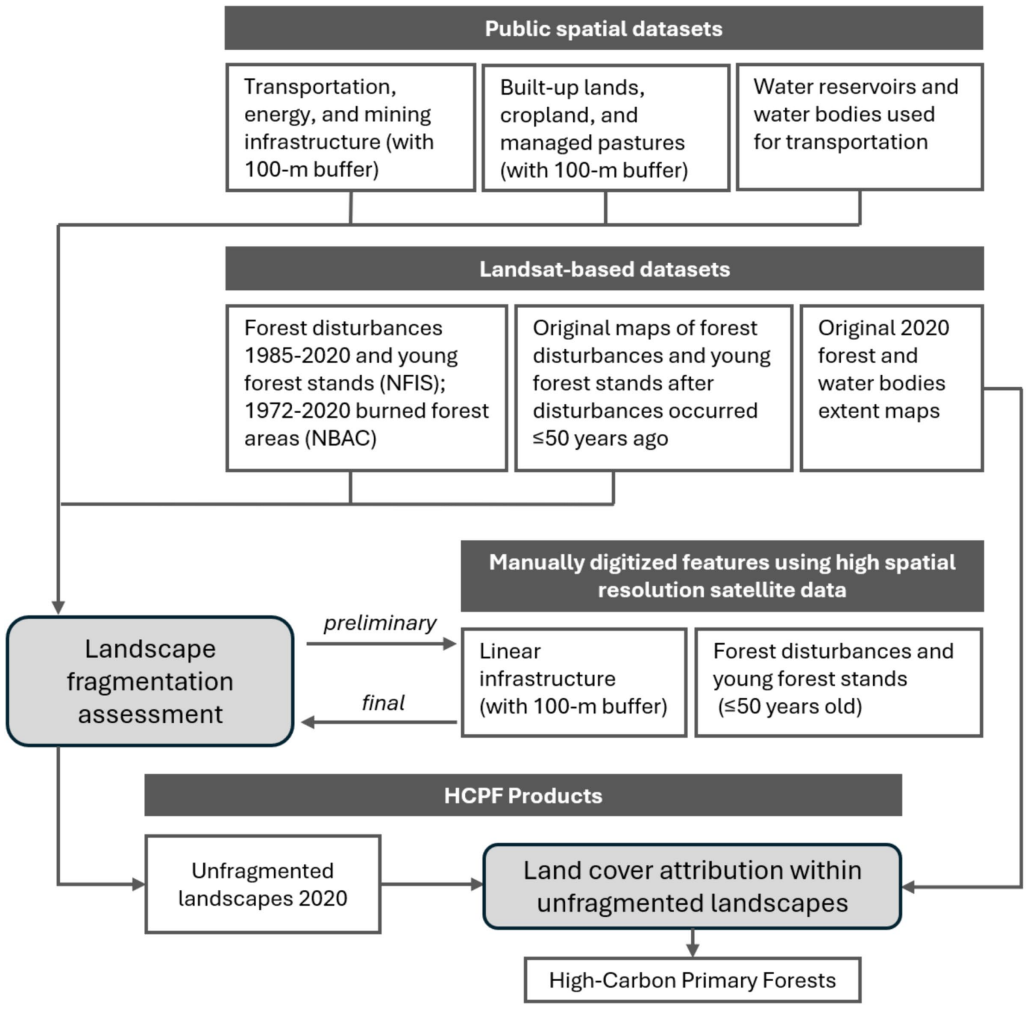


FIGURE 2
Unfragmented landscapes and high-carbon primary forests (HCPF) mapping workflow.

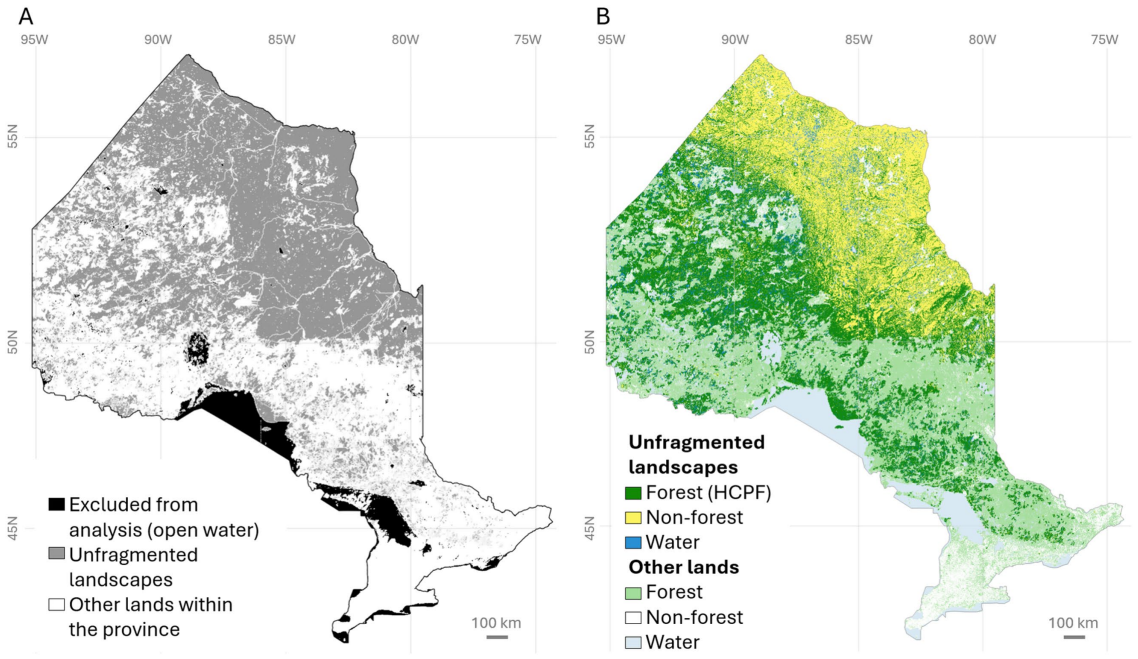


FIGURE 3
(A) Area of analysis within the province and selected unfragmented landscapes. Open water more than 500 m away from the closest land was excluded from the analysis. **(B)** Land cover attribution (forest, non-forest lands, and water) within and outside unfragmented landscapes in Ontario.

extracted from the National Burned Area Composite (NBAC; Skakun et al., 2022; Canadian Forest Service, 2024) to identify young forests regenerating after wildfires.

To complement NFIS forest disturbance data, we implemented an annual forest change mapping algorithm using Landsat data and a decision tree machine learning classifier, following the methodology outlined by Potapov et al. (2019, 2024). To map forest disturbance, we used annual change detection features extracted from the Landsat Analysis-Ready Data (Potapov et al., 2020). We implemented two forest disturbance mapping models, one to map stand-replacement disturbances defined as tree cover removal that affected 50% or more of a Landsat 30-m pixel, and another to map partial forest disturbances defined as tree canopy removal within less than 50% of a Landsat pixel. Partial disturbances typically include mixed pixels around stand-replacement disturbances, burned areas with partial tree mortality, and partial tree removals such as selection logging, strip cuts, and shelterwood cuts. Only substantial canopy disturbances are considered as partial disturbance category; individual tree mortality or light canopy damage that is not visible on Landsat 30-m data are excluded. Both change detection models were calibrated for Ontario using visually interpreted training data derived from Landsat image composites. These models were applied annually from 1985 to 2020 across the entire province.

To map forest regeneration pre-1985, we analyzed Landsat spectral reflectance changes between 1988, the first year with complete cloud-free Landsat data, and 2020. This analysis was conducted within the 2020 forest mask (Potapov et al., 2022a) and outside areas affected by stand-replacement and partial disturbance after 1985. We calibrated and implemented a machine learning model to map areas that had regenerated after pre-1985 disturbances and gained tree cover from 1988 to 2020. The model used Landsat-based land surface phenology features for 1988 and 2020, calculated using the approach of Potapov et al. (2020). To calibrate the model, we manually collected training data through visual interpretation of year 1988 imagery, 1988–2020 spectral change composites, and 1970s Landsat MSS images available in Google Earth Engine. We applied the model across the entire province to create per-pixel probabilities of regenerating forests. This layer was spatially filtered (to remove single-pixel noise) and manually cleaned to remove artifacts within wetlands and sparse tree cover areas.

We found that some disturbances, specifically selection logging within temperate forests, secondary forests after pre-1985 disturbances, as well as certain roads, such as private and unused roads, and seismic lines, were omitted from the existing datasets (Poley et al., 2022) and could not be consistently mapped using machine-learning classification. We performed a thorough visual assessment of the remaining unfragmented landscapes and manually mapped omitted fragmenting features and young secondary forests using the 1988 and 2020 Landsat image composites, the 2020 PlanetScope image mosaic (spatial resolution 4.8 m/pixel), and very high resolution (spatial resolution 0.5–1 m/pixel) image data freely available in Google Earth Pro. To reduce cost and increase the efficiency of visual analysis, a two-step approach was implemented. In the first step, we aggregated all fragmenting features from public datasets and Landsat-based forest disturbance and young stand maps. After excluding these fragmenting areas, we applied the 1,000-ha minimum patch size and 100-m minimum corridor criteria to produce a preliminary map of unfragmented landscapes. The second step involved visual assessment of the preliminary unfragmented patches. Transportation and mineral exploration infrastructure were mapped as linear objects, and disturbed and young forests were mapped as polygonal objects. More than 26,000 linear objects (road, power line, and seismic line segments) and more than 19,000 polygonal objects (selection logging and pre-1985 disturbances) were manually digitized through visual analysis. Following visual analysis, all identified fragmenting features were aggregated and excluded, and the fragmentation analysis was repeated to create the final unfragmented landscapes map (Figure 3A).

Although the visual interpretation step significantly delayed map production, it complemented automated mapping methods and existing maps and improved the map quality. After we excluded all manually interpreted infrastructure and disturbances, the total area of unfragmented landscapes decreased by 19%, illustrating the limitation of existing and automatically derived maps and the importance of thorough visual interpretation. By using a two-step analysis (in which visual interpretation was applied only within preliminary unfragmented areas mapped using existing maps), the area requiring visual analysis was reduced by 61%, demonstrating the effectiveness of this approach.

2.2.2 Land cover attribution of unfragmented landscapes

To attribute the land cover and map HCPF within unfragmented landscape patches, we employed the 2020 forest extent and water body maps. Forest extent was defined as areas with a tree height of 5 m or greater and tree canopy cover of 10% or greater at the Landsat pixel scale. The 2020 forest extent was derived from the Landsat-based tree canopy cover and tree height maps produced using the approach of Potapov et al. (2024). This mapping was conducted using Landsat Analysis-Ready Data, which were transformed into a set of annual land surface phenology features designed for land cover mapping (Potapov et al., 2020). First, the Landsat-scale tree canopy cover model was calibrated using the 10-m spatial resolution 2020 tree canopy cover map (Brandt et al., 2023). While the published product included only tropical forests, the World Resources Institute team processed a sample of extratropical reference data that we used to calibrate the Landsat-scale model in Canada. Second, the annual tree canopy cover map, limited to a canopy cover of 10% or greater to exclude non-forest areas, was used to extract tree height training data from two NASA spaceborne lidar instruments: Global Ecosystem Dynamics Investigation (GEDI; Dubayah et al., 2020) and Advanced Topographic Laser Altimeter System (ICESat-2/ATLAS; Neumann et al., 2019). We aggregated the 98% percentile vegetation height metrics from both instruments to calibrate our tree height model using the method developed by Potapov et al. (2021). We further used the 5 m tree height threshold combined with a tree canopy cover of 10% or greater to produce the forest extent map for Ontario. The water body map was extracted from the Landsat-based land cover and land use dataset (Potapov et al., 2022b). By overlaying the forest extent, water, and unfragmented landscapes datasets, we produced the final map of HCPF and other land cover types within unfragmented landscapes (Figure 3B).

2.3 HCPF dataset format

The 2020 Ontario unfragmented landscapes and HCPF maps are available online (see text footnote 1). The dataset is provided free of

charge and without restrictions on redistribution or use, provided that proper citation is given, as specified by the Creative Commons Attribution License (CC BY).

The map of unfragmented landscapes is provided in vector format using the EPSG 4326 (WGS 1984) coordinate system. The recommended visualization scale is 1:50,000. The map of land cover types within the unfragmented landscapes is provided in the raster data format with a pixel size of 0.00025 degrees. The 2020 HCPF map is also available as a Google Earth Engine data asset (projects/ee-potapovpeter/assets/Ontario_HCPF_2020).

2.4 HCPF distribution analysis and change monitoring

We analyzed the distribution of unfragmented landscapes and HCPF within Ontario using several reference datasets. The effect of forest management was evaluated using three categories (zones), including "managed and private lands" (comprising tenure and private lands), "protected and reserved lands" (protected, federal, First Nation reserves, treaty lands, and restricted lands), and "other lands" based on the map of forest management regions (Stinson et al., 2019). We excluded the "water" category from the analysis.

A detailed analysis of HCPF within forest management units (FMU) was done using the 2026 FMU database (Ontario Ministry of Natural Resources (OMNR), 2026). The ecosystem-level conservation target analysis was conducted using ecoregion and ecodistrict maps (Crins et al., 2009). To assess the HCPF distribution within woodland caribou habitat, we used caribou range boundaries (Ontario GeoHub, 2019) and calculated the percentage of 2020 unfragmented landscapes relative to total land area within each woodland caribou population range, excluding all water bodies.

We demonstrated the HCPF monitoring approach by integrating our 2020 HCPF map with the Global Forest Watch Tree Canopy Loss (TCL) dataset (Hansen et al., 2013). TCL is an annually updated product indicating tree cover loss events that affect at least 50% of the tree canopy within the Landsat pixel; for this analysis, we selected TCL for the years 2021–2025. According to the 1-km forest loss drivers product (Sims et al., 2025), most of the 2021–2025 TCL area in Ontario was due to wildfires (63.7%) and logging, including forest clearing for agriculture and urban expansion (35.3%). Less than 1% was attributed to other natural disturbances or unknown causes. Using the forest fire probabilities from Tyukavina et al. (2022), we separated the TCL of each year into non-fire-related and fire-related categories. We considered non-fire-related TCL as a proxy for the logging area. To create a conservative estimation of the logging area, we considered the low, medium, and high certainties of fire-related events from the Tyukavina et al. (2022) dataset as indicators of fire-related TCL.

To assess carbon stocks within unfragmented landscapes and HCPF, we used carbon stock maps produced for Canada at a 250 m resolution (Sothe et al., 2022a). Carbon stock maps were created using satellite imagery data from 2000 to 2019 and thus reflected recent changes in forests, such as forest fires. For the HCPF and non-HCPF forest analysis, we used the map of total carbon stored in the plants of forested areas in Canada, including aboveground, belowground biomass, and dead plant material carbon (Sothe et al., 2022b). We calculated the average carbon stock density using our forest mask within and outside HCPF areas for the province and each management zone. For the analysis of soil organic carbon (SOC), we used the Canada SOC map at the 0 to 1 m depth interval (Sothe et al., 2022c). We calculated the carbon SOC stock and stock density within unfragmented landscapes and other lands for the entire province. To assess the uncertainty of carbon stock density, we used Sothe et al. (2022a) 90% prediction confidence interval. These maps were created by calculating the per-pixel interval between the upper and lower prediction values obtained from the regression forest method. We calculate the average per-pixel prediction interval for each quantity and define uncertainty as half of the interval around the mean. We note that the uncertainty values provided by Sothe et al. (2022a) represent model prediction uncertainty, not map accuracy as assessed through independent validation data.

Detailed statistics of the 2020 HCPF area and their 2021–2025 change for management categories, ecoregions, ecodistricts, caribou ranges, and FMU are provided in Supplementary material.

3 Results

We found 2,285 patches of unfragmented landscapes (minimum area of 1,000 ha) within Ontario (Figure 3A). Unfragmented landscapes comprised more than half of the province's land area (58.4%, or 52.1 Mha) in the year 2020. Of this area, 54.5% was HCPF (forest within unfragmented landscapes), 39.2% was non-forest land, and 6.3% was lakes and rivers (Figure 3B). HCPF occupied 28.4 Mha, which was 48.2% of all forests within the province.

The distribution of HCPF by management zones was shaped by the history of land use conversion and forest disturbances over the past 50 years, including industrial logging and wildfires (Figure 4, Table 1). Low-productive northern forests in the "other lands" management zone (outside the zone of industrial logging) contain nearly half (48%) of the total HCPF area. More than 80% of the total forest area within this zone was attributed to HCPF. In contrast, managed and private lands contain 37% of all HCPF. This management zone has the lowest percentage of unfragmented landscapes relative to total land area, excluding water bodies (25.7%), and the lowest percentage of HCPF relative to total forest area (29.7%). Nearly 82% of young and fragmented (non-HCPF) forests of the province were found within this management zone. Protected and reserved lands have a higher percentage of HCPF (64.4%), but they include less than 15% of the total HCPF area within the province. The contrasting proportions of HCPF within and outside managed and private lands illustrate the direct effect of industrial logging on the maintenance of primary forests within the province.

Using the TCL and TCL due to fire datasets (Hansen et al., 2013; Tyukavina et al., 2022) from 2021 to 2025, we found that the HCPF area declined by 3.5% due to wildfires and industrial logging. The average rate of HCPF area reduction within Ontario was 0.2 Mha/yr. Non-fire-related TCL, which indicates logging, comprised 24% of the total HCPF loss area, and more than 95% of non-fire-related TCL was found within managed and private lands, where industrial logging is allowed. The remaining HCPF within these lands have been targeted for logging as they generally contain the most valuable timber resources. Within this management zone, 2.2% of HCPF and 1.7% of non-HCPF forests were logged between 2021 and 2025 (Table 1). The percentage of HCPF logging within other management zones was much lower than within managed and private lands (Table 1).

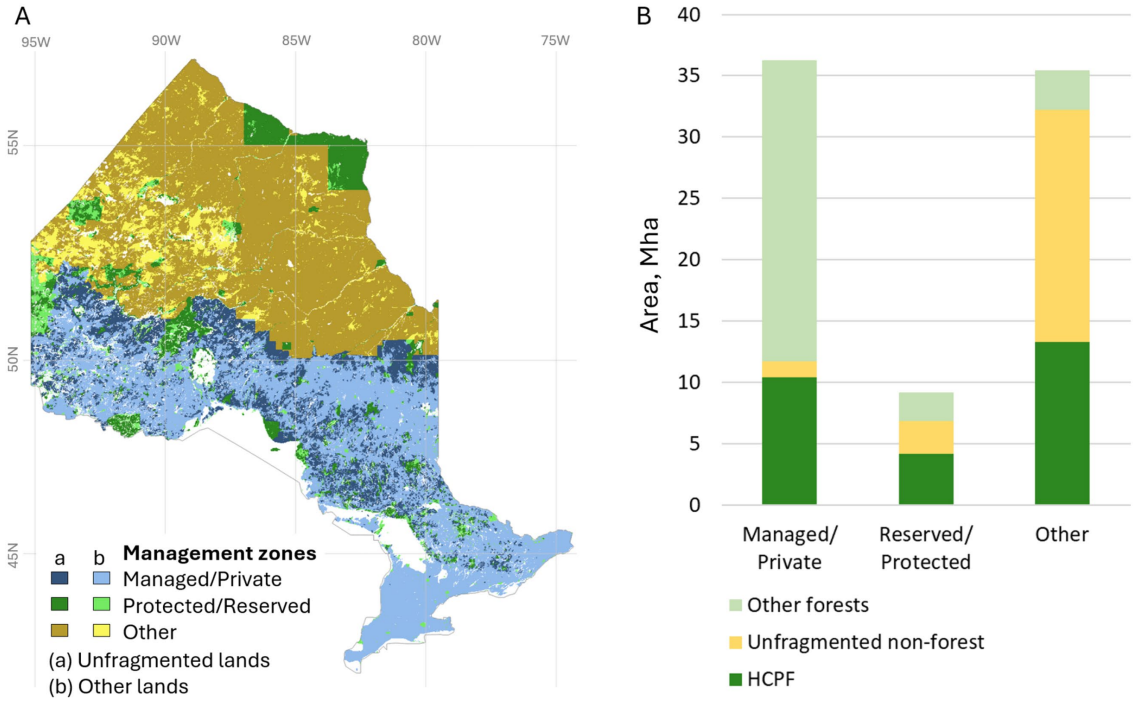


FIGURE 4
(A) Distribution of unfragmented landscapes within forest management zones based on the map of forest management regions by Stinson et al. (2019). **(B)** Area of HCPF, unfragmented non-forest areas, and other (non-HCPF) forests within each management zone, Mha.

TABLE 1 HCPF percentage, disturbance rate, and mean forest carbon stock density (with a 90% prediction confidence interval) by each management zone.

Management zone	2020 HCPF percentage of the total forest area	Percentage of non-fire-related tree cover loss 2021–2025 within 2020 HCPF	Forest carbon stock density, Mg/ha	
			Non-HCPF forests	HCPF
Managed/private	29.7	2.2	52.8±17.4	62.3±20.5
Reserved/protected	64.4	0.2	46.3±15.7	58.2±19.5
Other	80.7	0.03	29.2±10.9	44.8±16.3
Entire province	48.2	0.8	49.8±16.6	53.3±18.3

Management zone boundaries are based on the forest management regions map by Stinson et al. (2019); water area from the forest management map is excluded from this analysis. Forest carbon stock density data from Sothe et al. (2022a).

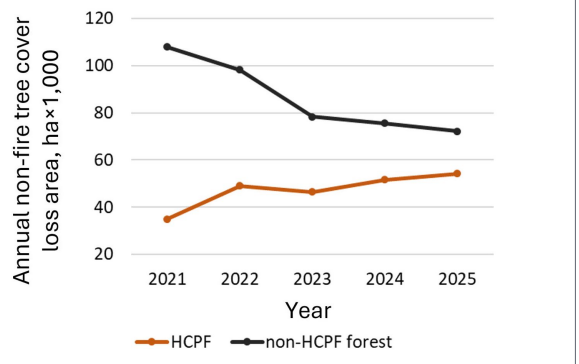


FIGURE 5
Annual non-fire-related tree cover loss 2021–2025 within HCPF and non-HCPF forests.

The annual non-fire-related TCL (annual logging area) in Ontario decreased by 12% (from 143,000 to 126,000 ha) from 2021 to 2025. However, the annual logging area dynamics were different between HCPF and non-HCPF forests. While non-fire-related TCL decreased in non-HCPF forests by 33%, it increased within HCPF by 55% (Figure 5). By 2025, 43% of all timber harvesting in Ontario occurred within the remaining HCPF, illustrating the accelerating threat of HCPF loss within industrially managed forests.

To better understand the nature of HCPF and their dynamics at a finer resolution throughout the province, we focused on three ecosystem management objectives: (1) *understand nature* by analyzing HCPF distribution within ecoregions and ecodistricts, (2) *manage nature for economic benefit*, including logging and fire within logging concessions, and (3) *monitor and maintain self-sustaining wildlife populations*, including species-at-risk such as woodland caribou.

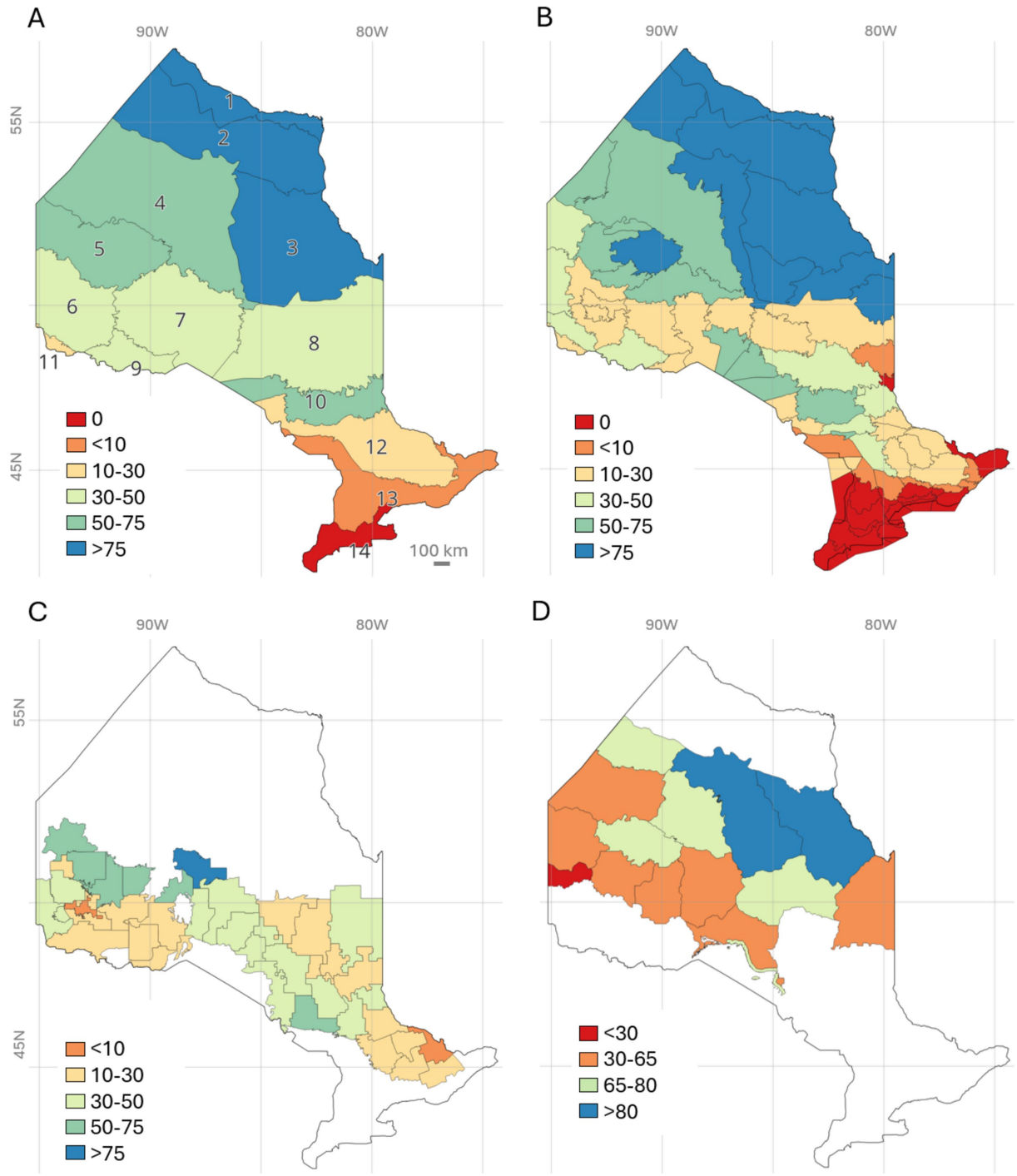


FIGURE 6
HCPF 2020 percentage of total forest for: **(A)** ecoregions (see Table 2 for ecoregion codes), **(B)** ecodistricts, and **(C)** forest management unit (FMU). **(D)** Unfragmented woodland caribou habitat (% of 2020 unfragmented landscapes of total land area; water bodies excluded) in caribou ranges.

3.1 HCPF distribution by ecoregions and ecodistricts

The distribution of HCPF percentage across ecoregions and ecodistricts varies extensively and reflects land use and forest management history (Figures 6A,B, Table 2). At the ecoregion level, the HCPF percentage of the total forest area ranges from > 90% in the Hudson Bay Lowlands of northern Ontario (ecoregions 1, 2, and 3 in Table 2 and Figure 6A) to less than 2% in the most southern Mixedwood Plains (ecoregions 13 and 14 in Table 2 and Figure 6A).

At the ecodistrict level (Figure 6B), there was a noticeable difference in HCPF percentage among the southern, central, and northern parts of the province, showing a general trend of increasing HCPF proportion from south to north. In southern Ontario (south of ~45°N), where most forests have been converted to non-forest land use (Quinby et al., 2022), we did not find significant unfragmented

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TABLE 2 Unfragmented landscapes, HCPF, and tree cover loss within HCPF for each ecoregion.

Ecoregion	Unfragmented landscape area (2020), ha×1,000	HCPF 2020		Non-fire-related tree cover loss 2021–2025 within HCPF	
		Area, ha×1,000	Percentage of total forest area	Area, ha×1,000	Percentage of the 2020 HCPF
Hudson Bay Coast (1)	2680.9	246.0	96.0	0.01	0.002
Northern Taiga (2)	8748.2	1557.2	92.5	0.03	0.002
James Bay (3)	11836.3	3923.7	94.4	0.77	0.02
Big Trout Lake (4)	11239.3	7736.1	73.5	7.96	0.10
Lake St. Joseph (5)	4062.2	3417.2	66.2	15.86	0.46
Lake Wabigoon (6)	1518.0	1256.8	30.1	25.05	1.99
Lake Nipigon (7)	3116.8	2704.2	39.0	50.98	1.89
Lake Abitibi (8)	4480.8	3591.9	31.7	85.76	2.39
Pigeon River (9)	622.4	534.6	33.5	10.92	2.04
Lake Temagami (10)	1953.0	1780.5	50.8	29.12	1.64
Agassiz Clay Plain (11)	35.5	26.4	12.6	0.03	0.12
Georgian Bay (12)	1746.4	1578.9	25.0	9.22	0.58
Lake Simcoe- Rideau (13)	65.2	58.6	2.2	0.54	0.91
Lake Erie - Lake Ontario (14)	0	0	0	0	N/A

The ecoregion map is from Crins et al. (2009); the ecoregion names include numeric indices used in Figure 6A.

landscapes except within large wetlands. In the central part of the province, roughly between 45° and 48°N, extensive logging occurred prior to the 1970s, including portions that were only affected by logging in the late 19th and early 20th centuries. As a result, some ecodistricts in this area have ≥ 30% HCPF, including significant amounts of mature secondary forests older than 50 years. In contrast, the northern portion of the commercial forest management zone (between 48°N and 51°N) has been targeted by industrial logging expansion over the past 50 years, decreasing the percentage of HCPF to as little as 10-30%. Ecodistricts north of the commercial forest management zone have the highest percentage of remaining HCPF.

3.2 HCPF distribution by forest management units

The analysis of HCPF percentage by forest management units (FMU) highlights areas where forests were historically converted into other land uses and where industrial logging has been expanding since the 1970s (Figure 6C). Of all FMU within Ontario, almost half (19 out of 39) contain less than 30% HCPF of total forested area, including the Algonquin Park FMU with only 26.7% HCPF. The lowest percentage of HCPF (<10%) was found within the Ottawa Valley and Dryden FMU.

The percentage of 2021–2025 non-fire-related TCL within each FMU revealed hotspots of recent logging expansion within unfragmented forests (Figure 7). The following FMU had an HCPF logging rate of more than 1% per year: Dog River-Matawin, Dryden, English River, Nagagami, Pineland, and Timiskaming. The Dryden FMU lost HCPF at a rate of more than 2% per year. Within the English River FMU, which lost 5.5% of its HCPF over the past five years, a portion of new logging occurred within the Brightsand woodland caribou range, indicating potential conflict with habitat preservation.

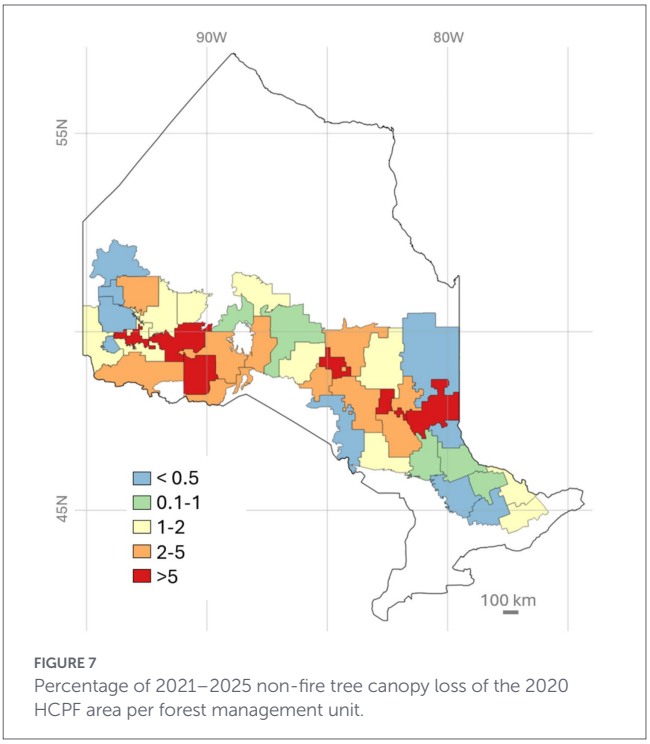


FIGURE 7
Percentage of 2021–2025 non-fire tree canopy loss of the 2020 HCPF area per forest management unit.

Many FMU have increased industrial logging within HCPF over the past five years. Among those, the Black Spruce, Nagagami, and Timiskaming FMU more than doubled their average annual logging area within HCPF from 2021through 2025.

3.3 HCPF distribution by woodland caribou ranges

Forests and wetlands that have not been burned or logged for at least 50 years are considered high-quality winter feeding grounds required for the survival of woodland caribou (Joly et al., 2012; Palm et al., 2022). The recovery strategy for boreal caribou (ECCC, 2020) identifies 65% undisturbed habitat within each range as the disturbance management threshold, or minimum needed for a 60% probability of a self-sustaining population. The 65% undisturbed habitat is considered a minimum threshold because even when it is reached, there remains a significant risk (40%) that local populations will not be self-sustaining (ECCC, 2020).

To analyze the availability of undisturbed habitat within Ontario, we calculated the percentage of 2020 unfragmented landscapes, which includes both forest and non-forest areas such as wetlands and open peatlands that caribou depend on for foraging, relative to total land area within each woodland caribou population range, excluding all water bodies from this analysis (Figure 6D). We found that the percentage of unfragmented landscapes was below 65% in 8 out of 15 population ranges in Ontario. The lowest unfragmented landscapes percentage was in Berens (48%) and Sydney (23%) ranges, indicating a shortage of mature and old-growth habitat for winter feeding. Continuing logging and wildfires increasingly threaten the loss of remaining HCPF within all of Ontario's caribou ranges. For example, from 2021 to 2025, HCPF areas decreased by 17% in the Berens range and by 28% in the Sydney range due to wildfires and logging. The highest HCPF reduction due to industrial logging alone (1.9%) was found in the Churchill and Brightsand ranges, illustrating the conflict between industrial forest management and caribou habitat protection.

3.4 HCPF carbon stock

Using an Ontario subset of the map of total carbon stored in the plants of forested areas in Canada (Sothe et al., 2022b), we found that the carbon stock density was higher within than outside HCPF for the entire province and each of the three management zones (Table 1). The higher carbon stock density within HCPF may be explained by the presence of mature and old-growth forests that have been accumulating biomass over longer periods than younger non-HCPF forests. Within the managed and private forests, younger non-HCPF forests regrowing after industrial logging store on average 18% less carbon per unit area compared to mature and old-growth HCPF forests. The highest difference was found for the northern forests outside the industrial logging zone, where the average carbon stock density was 54% higher within HCPF compared to non-HCPF forests. Such a high difference can be explained by the low carbon stock density within recently burned non-HCPF forests that regenerate slowly in the northern part of the province.

The unfragmented landscapes, including forest and non-forest ecosystems, play an important role in protecting the long-term soil carbon pool due to the co-occurrence of unfragmented areas with northern peatlands. We used the Canada map of soil organic carbon (SOC) at the 0 to 1 m depth interval (Sothe et al., 2022c) to estimate the average SOC within and outside unfragmented landscapes. We found that the average SOC within unfragmented landscapes (805.2 ± 254.3 Mg/ha) was more than twice as high as the rest of the province (367.1 ± 139.1 Mg/ha). Such a large difference is explained by the high proportion of peatlands that are included within unfragmented landscapes in the north of the province. Both forest carbon and SOC analysis confirmed the importance of unfragmented landscapes and HCPF in protecting long-term carbon stocks.

4 Discussion

4.1 HCPF as conservation targets

Ontario has a well-developed system of parks and nature reserves that makes up about 11.2% of the province (ECCC, 2026). This percentage represents roughly a third of the 30% protection required by the Kunming-Montréal Global Biodiversity Framework's Target 3, adopted by Canada (ECCC, 2024). Expansion of the protected areas system should prioritize natural ecosystems important for biodiversity and ecosystem functions and services, consider threats to remaining natural ecosystems, and account for the cost of protection. Protected areas system should also support climate change mitigation by ensuring ecosystem resilience to increased natural disturbance rate and intensity and supporting species migration and ecosystem adaptation. A mechanism to assess and monitor the conservation value of potential protected areas is therefore needed to ensure the effectiveness and robustness of future protected areas systems.

The unfragmented landscapes and HCPF approach provides a simple and practical tool for mapping, prioritizing, and monitoring conservation targets at provincial and national scales using publicly available data such as satellite image archives. It builds upon and improves the landscape fragmentation methodologies of Potapov et al. (2017), Quinby et al. (2022), and Mackey et al. (2024) by using the smallest practical unfragmented patch size for provincial-level analysis (1,000 ha) and by implementing a detailed analysis of a long satellite data time series that ensures the exclusion of most disturbances over the past half-century and all fragmenting infrastructure. Our approach prioritizes the protection of unfragmented landscapes that maintain ecosystem integrity and resilience. Such landscapes represent undisturbed habitats required to protect most wildlife species, including woodland caribou. Soil organic carbon (SOC) dominates terrestrial carbon stock in Canada (Sothe et al., 2022c), and more than 72% of the total SOC is stored within unfragmented landscapes, highlighting their role in climate regulation. Mapped HCPF represent the subset of primary forests with the highest conservation value within the province that are irreplaceable for biodiversity support and climate regulation, but vulnerable to industrial logging and the increasing wildfire frequency.

Mature and old-growth forests are important components of the landscape matrix. These forests support populations of species that depend on late-successional habitat and disturbance refugia (Bouchard and Pothier, 2011; Morales-Hidalgo et al., 2015; Bergeron et al., 2017; Grondin et al., 2018; Gilani and Innes, 2020; Martin et al., 2021) and preserve the genetic diversity of tree species (Mosseler et al., 2003). Loss and fragmentation of forest landscapes by infrastructure, mining, and logging have been shown to reduce habitat capacity for many wildlife species, including woodland caribou (Joly et al., 2012; Palm et al., 2022), highlighting the urgent need for HCPF protection within caribou population

ranges. Late-successional communities serve as indicators of ecosystem health (OMNR, 2003a) and as benchmarks that guide forest restoration (Quinby, 1991). More frequent and intensive fires under a changing climate (Hanes et al., 2019), together with increasing industrial logging, have reduced and may potentially eliminate late-successional forests in Canada (Whitman et al., 2019; Larocque et al., 2024).

The protection of remaining HCPF is an effective climate mitigation strategy, given their significant role in regulating the global carbon cycle. A recent study by Pascual et al. (2026) showed that boreal primary forests may store 72% more carbon compared to managed secondary forests if all carbon pools are considered. Mature and old-growth forests support climate regulation through carbon sequestration and long-term carbon storage (Luyssaert et al., 2008). Their conservation is considered one of the most effective natural climate solutions to reduce atmospheric CO_2 (Drever et al., 2021). Our analysis confirmed that HCPF have higher carbon density compared to young, managed, and fragmented forests. The analysis of SOC distribution showed that most of the soil carbon in Ontario is stored within unfragmented landscapes. Our findings confirm the importance of unfragmented landscapes and HCPF for carbon sequestration and climate regulation.

The HCPF definition excludes young primary forests regenerating after natural disturbances. We suggest that the inclusion of young forests as conservation targets may complicate the mapping methodology and weaken conservation policy development and application. First, accurate identification of historic forest loss drivers (before 1985) using publicly available maps and satellite data may be impossible or highly uncertain due to the spatial coincidence of fires and logging. Second, the inclusion of young forests as conservation targets may divert attention from mature and old-growth forests, accelerating the decline of the latter. Our analysis demonstrates that HCPF have been targeted by industrial logging, and their area within commercially managed lands is declining. If conservation targets include landscapes with a large proportion of young forests, it will likely be difficult to achieve a compromise with industrial logging interests to protect the remaining HCPF, which is the most valuable conservation target.

Low levels of landscape fragmentation by infrastructure and industrial logging provide a good proxy for ecosystem intactness and integrity, which are associated with high conservation values (Balmford et al., 2002; Luyssaert et al., 2008; Gauthier et al., 2015; Potapov et al., 2017; Grantham et al., 2020). Large, unfragmented landscapes maintain populations of wide-ranging species, support large-scale natural disturbance dynamics, and provide ecosystem resilience (Laurance et al., 2002; Potapov et al., 2017). High ecosystem integrity, typical of large unfragmented landscapes, supports climate adaptation through migration pathways and high genetic diversity that allow ecosystems to change and populations to adapt while preserving structure, function, and composition, including species diversity.

Ongoing fragmentation of forested landscapes threatens ecosystem integrity even when the total forest area is not reduced. Once a landscape is fragmented, its intactness and integrity are difficult or impossible to restore (Mackey et al., 2015; Potapov et al., 2017). Meanwhile, the cost of protection for a large unfragmented landscape is lower compared to the cost of forest restoration or protected area establishment within a highly fragmented landscape. While the protection of HCPF will result in lost revenue from timber and mineral extraction (Zwerts et al., 2024), the limited human access and large extent of the protected area will ensure its resilience to edge effects, stand-level natural disturbances, and climate change (Yaroshenko et al., 2001; Potapov et al., 2008). Protection of HCPF may also facilitate natural ecosystem restoration within adjacent disturbed and managed lands.

Within FMUs where HCPF comprises less than 30% of the forested area, the scarcity of remaining primary forests suggests that all HCPF patches warrant protection. This threshold is consistent with the scale of ambition reflected in Target 3 of the Kunming-Montréal Global Biodiversity Framework, though we note that Target 3 applies to national-level protection rather than per-unit forest management. For the remaining FMU, a detailed analysis of HCPF and conservation prioritization is needed to prevent further loss of wildlife species habitat, rare ecosystems, and old-growth forests. We propose three criteria to select HCPF with the highest conservation priority: (1) HCPF with the largest extent, since large unfragmented patches have higher integrity and resilience, sustain a larger number of species by encompassing a large variety of habitats, and require lower conservation costs compared to small patches, (2) HCPF reduction rate (assessed from the 2021–2025 logging area), since patches with the highest reduction rate are under immediate threat from industrial logging, and (3) the presence of high conservation value indicators such as rare species habitat, old-growth forests, and late successional disturbance refugia. The indicators for criterion 3 can be identified by integrating HCPF with other spatial datasets (Red List species distributions, old-growth forests maps), through satellite data analysis (e.g., to detect late-successional forest types such as eastern hemlock forests; Quinby, 2025), and through field assessment (Quinby and Marcus, 2026). The relative importance of these three conservation prioritization criteria should be determined based on local context. Other indicators, estimated directly from the HCPF map or through integration with other datasets, may include HCPF patch shape, location, connectivity, and carbon stock.

4.2 HCPF map accuracy and known limitations

We did not perform a formal validation of the unfragmented landscapes and HCPF maps. The minimum patch size implemented for the fragmentation analysis and the use of the official infrastructure and land cover maps precluded the application of standard sample-based validation methods (e.g., Olofsson et al., 2014). The absence of formal validation of the forest fragmentation maps derived from existing datasets is typical for similar regional and global assessments (Potapov et al., 2017; Grantham et al., 2020; Quinby et al., 2022; Mackey et al., 2024). We argue that the detailed visual assessment applied to the entire province to detect infrastructure and forest disturbances using high-resolution satellite data renders additional sample-based map validation largely unnecessary.

We suggest, however, that our landscape fragmentation analysis may have been affected by potential errors from two main sources. First, gaps and errors in the publicly available maps may introduce commission errors to the unfragmented landscapes map (Poley et al., 2022). We minimized this error through a detailed visual analysis; however, analysts may still omit historically disturbed forests and small roads due to the lack of satellite data before 1985 and the

inability to map roads hidden by forest canopy. Second, the detection of pre-1985 forest disturbances has lower sensitivity compared to post-1985 disturbances, especially in the mixed forests of southern and central Ontario. This limitation may have effectively reduced the mature forest age threshold from 50 to 40 years for some mixed and broadleaf forests.

The uncertainties of our Landsat-based tree canopy cover and height maps may have affected the forest extent attribution within unfragmented landscapes. However, we do not expect significant errors related to the forest extent as this map has user's and producer's accuracy above 94% at the global scale (Potapov et al., 2022b). The total forest area estimated using our 2020 map was very similar (0.2% difference) to the area of the tree canopy cover class derived from the ESA WorldCover 2021 (Zanaga et al., 2022) and was 7% lower than the satellite-based forest area reported by Wulder et al. (2020). Our Landsat-based forest area estimate is, however, substantially lower than the forest area reported by OMNR (2021), which includes temporary treeless areas after wildfires and clearcuts.

Finally, we must point out the shortcomings of the HCPF definition, which considers only a subset of primary forests that are older than 50 years and are located within large (1,000 ha or more) unfragmented landscape patches. Our definition excludes young forests naturally regenerating after disturbances, such as wildfires. The HCPF dataset does not include small fragments of natural forest within historically transformed parts of the province, where different approaches for conservation prioritization are needed. At the same time, HCPF may include forests affected by logging that occurred more than 50 years ago, even when the long-lasting effects of logging are detectable in the field. The analysis did not produce a map of "pristine" forests, but the method supports a framework for further site-specific verification to identify such forests within HCPF patches using field-based methods, such as those proposed by Quinby and Marcus (2026), lidar-based late-successional forest mapping (Hagan et al., 2026), and the analysis of historical forest management documents (forest management plans and logging concession maps). Such approaches, while important at the local scale, cannot be implemented consistently across the entire province due to their high cost and the lack of publicly available historical documents.

5 Conclusion

Building upon established methods for mapping forest conservation targets (Potapov et al., 2017; Quinby et al., 2022; Mackey et al., 2024), we present a definition, mapping methodology, and monitoring approach for high-carbon primary forests (HCPF). The HCPF definition includes mature and old-growth forests (≥50 years old) within unfragmented landscape patches ≥1,000 ha. HCPF are not equivalent to 'pristine' primary forests: they (a) exclude areas recently affected by natural disturbances, (b) exclude small undisturbed forest patches within developed landscapes, and (c) may include areas affected by logging more than 50 years ago. Rather, HCPF represent patches of old-growth and mature naturally regenerated forests with high conservation value, characterized by high carbon storage, woodland caribou habitat, late-successional species refugia, and other ecosystem functions and services. The HCPF map provides a framework for detailed analysis of primary and old-growth forest distribution within unfragmented and recently undisturbed landscapes, supporting forest management and conservation planning. HCPF mapping and monitoring relies on remote sensing data, combining automated processing with visual image interpretation. Applying the proposed definition and methodology, we provide 2020 unfragmented landscapes and HCPF maps for Ontario (see text footnote 1). The same criteria and methodology can be extended to other Canadian provinces to establish a nationally consistent forest conservation target and undisturbed forest monitoring baseline.

Our analysis showed that while HCPF comprise almost half of the province's forest area, their percentage within managed and private lands is smaller (29.7%). Less than 15% of the total HCPF area is located within protected and reserved lands. We confirmed that HCPF have higher carbon stock density compared to younger and fragmented forests. We also showed that unfragmented landscapes contain more than 72% of the soil organic carbon stock within the province due to co-occurrence of HCPF with peatlands, illustrating their unique role in climate regulation. Unfragmented landscapes are important as woodland caribou winter feeding grounds, but their proportion in most ranges is below the 65% management threshold (ECCC, 2020), which may affect population survival. The remaining HCPF are shrinking fast due to the compound effect of industrial logging and increasing wildfires. Over the last five years (2021–2025), HCPF lost 3.5% of their area, while the logging intensity within the remaining HCPF increased by 55%. Within some FMU, HCPF area decreased by 1%–2% per year, which supports the urgent need for mature and old-growth forest protection within managed and private forests of Ontario.

In regions with scarce HCPF (less than 30%), we recommend that all remaining HCPF should be protected, given their importance for climate mitigation and maintaining ecosystem integrity. In other regions, HCPF maps and change analysis support forest land prioritization based on the quantifiable conservation value of individual HCPF patches. We suggest that the following patch features may be used to prioritize sites for protection: location, size, composition (e.g., representation, rarity, species-at-risk), shape, connectivity, threats, and forest loss rate over the past 5 years. The HCPF method creates a framework for satellite-based and field-based mapping of old-growth forests and disturbance refugia to highlight conservation priority sites. These capabilities can support the development of effective policies to protect primary forests at the Ontario provincial level and can be easily adapted to other forested landscapes. The HCPF mapping and monitoring approach was successfully demonstrated in Ontario and may be implemented at the national scale to support high conservation primary forest protection in Canada.

Finally, by addressing HCPF in the context of FMU, future studies will be able to relate the dynamics of HCPF and wildlife populations (e.g., woodland caribou) to economic and social metrics through access to sustainable forest licensee annual reporting and other licensee data. The links between ecosystem health and industrial resource extraction are poorly understood and urgently needed. Developing a better understanding of these linkages is timely, given the current unprecedented threats to the health of the biosphere, including the accelerating loss of primary forests.

Data availability statement

The unfragmented landscapes and HCPF datasets are available online at https://zenodo.org/records/18565690. The source datasets used in this study can be found in online repositories.

Author contributions

PP: Writing – review & editing, Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Data curation. ST: Investigation, Writing – original draft, Formal analysis, Writing – review & editing, Conceptualization. PQ: Conceptualization, Writing – review & editing. AY: Conceptualization, Writing – review & editing. JB: Data curation, Writing – review & editing. AH-S: Writing – review & editing, Visualization. AT: Writing – review & editing. EG: Conceptualization, Writing – review & editing. NH: Writing – review & editing, Conceptualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author PP declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2026.1871841/full#supplementary-material

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