Mapping Structurally Stable Natural Forests in Canada

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1. Background and Context

Canadian forests have been affected by human activity for thousands of years. Their distribution, composition, structure, and dynamics are shaped by historical and current human activities, ranging from local management practices to widespread climate change effects. Although there are no completely untouched forests in Canada (NRC, 2025), a significant portion of forest ecosystems remain only minimally affected by human activity, sustaining natural species diversity and dynamics. Over the last decades, several projects have aimed to map these areas - often called old-growth, primary, or intact forests. However, a lack of consensus on definitions, mapping methods, and the extent of these areas in Canada hinders the development and application of conservation policies.

WWF-Canada's work on primary forests includes developing an understanding of the criteria used to define primary forests, creating a spatial framework for mapping these forests, and facilitating dialogue among civil society, forest management, Indigenous organizations, and research communities regarding perspectives on primary forests and associated mapping efforts. As part of this project, WWF-Canada has partnered with Habitat (an environmental solutions company) and with the University of Maryland's Global Land Analysis and Discovery (GLAD) laboratory for project components related to definitions and mapping.

Habitat conducted a review of the current state of knowledge for defining, identifying and classifying primary forests in Canada and proposed the following definition for primary forests in Canada: "forests of any age class, composed of naturally regenerated native species, undergoing natural ecological processes and subjected to natural forest disturbance dynamics, that have not been impacted by anthropogenic disturbances or usage other than traditional land use" (Habitat, 2024).

The GLAD laboratory is a center of global expertise in forest monitoring using satellite imagery. They developed a humid tropical primary forest layer for 2001 that is used as a reference for assessing deforestation rates pan-tropically. This report documents the University of Maryland's methodology for developing a prototype map of the Structurally Stable Natural Forest (SSNF) in Canada, related to the tropical primary forest mapping methodology. The results include a series of thematic layers that allow for analysis and integration based on user-defined criteria.

2. Definitions and Objective

The definition of primary forests used for satellite-based mapping is usually equivalent to the recently undisturbed mature natural forests. For example, Turubanova et al. (2018) defined humid tropical primary forests as "mature natural … forest cover that has not been completely cleared and regrown in recent history". This definition partially aligns with the primary forest definition recommended by Habitat, but it excludes forests recovering from natural disturbances like fires, insects, diseases, floods, or winds. Conversely, it includes natural mature forests that have been impacted by historic disturbances, if those impacts cannot be detected using modern satellite imagery. In temperate forests, this definition might even include mature plantations of native tree species that were established long ago and have not been intensively managed in recent decades. The spectral properties of these mature plantations can be indistinguishable from those of natural forests when using moderate-resolution satellite data, such as Landsat.

The long history of forest management in Canada complicates the satellite-based delineation of the remaining undisturbed forest patches within a mix of secondary forests and tree plantations of different ages. The use of fragmentation criteria may help simplify primary forest mapping within historically developed temperate forests. While there is no agreement on these criteria, we propose to use a mapping framework that allows testing different thresholds and fragmentation drivers.

We define a Structurally Stable Natural Forest (SSNF) as mature forests composed of native tree species that have not experienced intensive disturbances in the last three to five decades and are minimally fragmented by intensive land management and infrastructure. The objective of this work is to provide a set of thematic layers that can be combined to map the extent of SSNF in Canada. These layers include forest extent, forest disturbance, intensively managed lands, built-up areas, and infrastructure. The layers in this flexible mapping framework can be combined using various rules and thresholds to support further data analysis and discussions.

3. Methods

3.1. Forest Extent Mapping

We derived the 2020 forest extent from new global woody vegetation structure time series maps created by our team. This mapping was done at the continental scale using Landsat Analysts Ready Data, which were transformed into a set of annual land surface phenology features designed for land cover mapping (Potapov et al., 2020). First, we calibrated the woody vegetation canopy cover model using a recently published 10 metre/pixel tree canopy cover product for 2020 from the World Resource Institute (Brandt et al., 2023). The WRI team processed a sample of extratropical reference data that we used to calibrate the Landsat-scale model in Canada. Second, the annual woody vegetation cover map, thresholded at 10% canopy cover to exclude non-forest areas, was used to extract tree height training data from NASA's GEDI (Dubayah et al., 2020) and ICESat-2 ATLAS (Neumann et al., 2019) spaceborne lidar instruments. We used the GEDI RH98 metric (98th percentile of returned energy), which represents the top of the vegetation canopy within the GEDI footprint (Lag et al., 2023). The only metric available for the 20-meter ICESat-2 ATLAS orbital track segments is the 98% relative canopy height, which is similar to the GEDI RH98. The data from both GEDI and ATLAS instruments were combined into a single reference dataset that we used to calibrate our woody vegetation height model. This model was applied annually from 2015 to 2023 within the areas with tree canopy cover of the same year ≥10%. The resulting annual tree height maps were filtered to reduce inter-annual noise.

The forest extent map for Canada was defined as areas with modeled tree heights of 5 m or greater and tree canopy cover of at least 10% in 2020. The forest mask generated using our methodology closely resembles the forest extent map from the ESA WorldCover 2021 dataset and the forest extent mapped by Natural Resources Canada (Maltman et al., 2023) (Fig. 1). .

We mapped 354 million ha of forests compared to 347 million ha reported by the FAO (FAO 2020). The area classified as forest in our map is 2% higher compared to the FAO 2020 report. The main disagreements with the Natural Resources Canada (Maltman et al., 2023) map were found in the forest/tundra ecotone and within scattered tree stands in urban and intensively managed agricultural landscapes. The primary reason for disagreement between our map, the FAO reporting, and the map developed by the Natural Resources Canada is that our map defines forest class by the presence of trees, while the FAO and NRC consider trees within non-forest land use as trees outside forests.

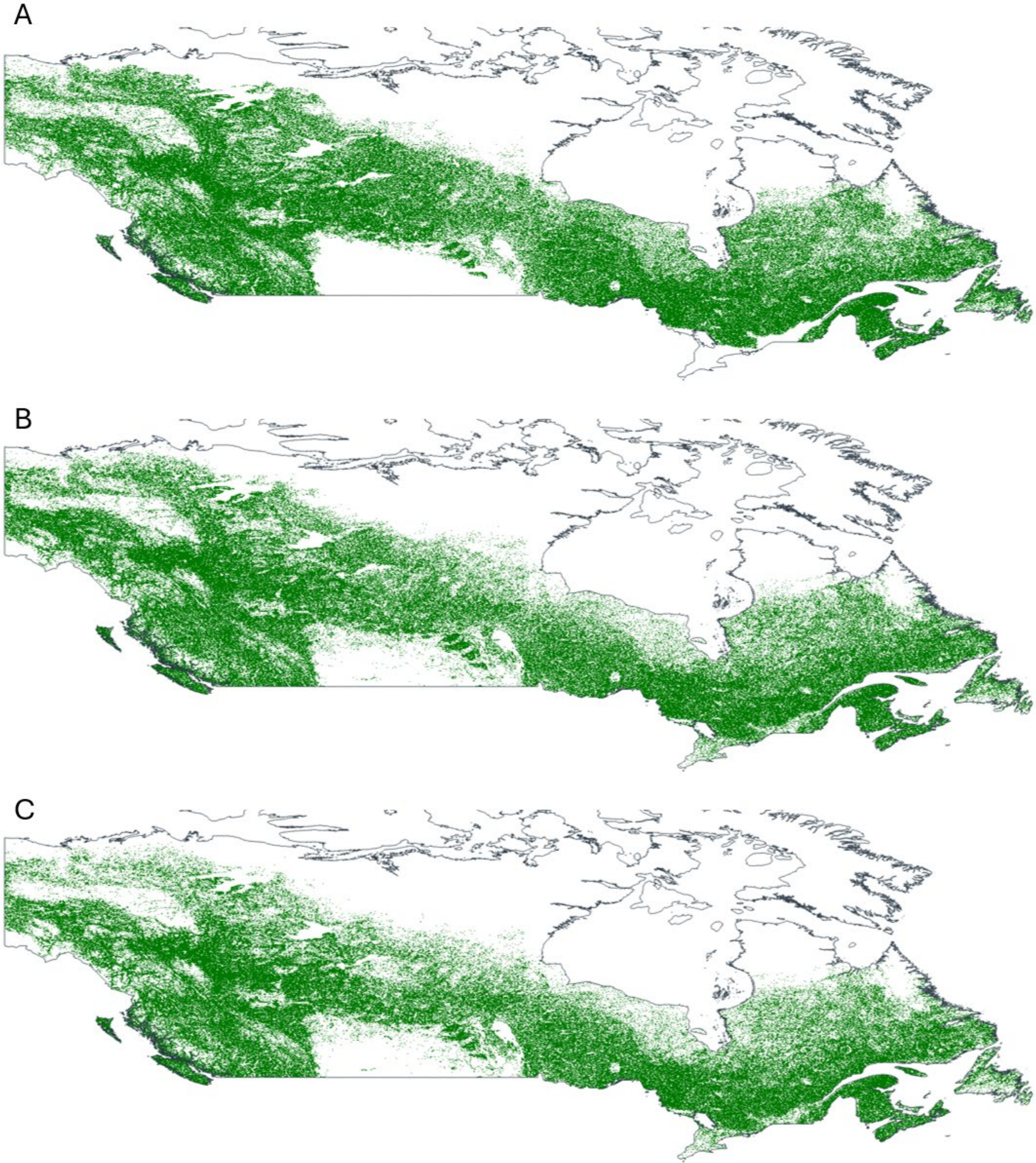


Figure 1. A – Extent of forests of all ages in Canada, 2019 (Maltman et al., 2023); B - Canada forest extent according to ESA WorldCover 2021. C - Canada forest extent 2020 produced for this project. For all maps, forests are shown in green and non-forest areas in white.

3.2. Forest Disturbance Mapping.

The forest disturbance layers are categorized into three types: (1) stand-replacement disturbances from 1985 to 2020, (2) partial tree canopy loss at 30 m resolution from 1985 to 2020, and (3) forest stands recovering from disturbances that occurred before 1985. It is important to note that the disturbance data does not distinguish between natural and anthropogenic drivers.

We define stand-replacement forest disturbance as an event of complete and near-complete removal of tree canopy within a 30-m pixel, caused by either natural factors (fire, wind, flood, insects, diseases) or mechanical tree removal (timber harvesting or land use conversion). The annual forest disturbance mapping algorithm is based on the principles outlined by Potapov et al. (2019). To map forest disturbance, we used annual change detection features extracted from the Landsat ARD dataset (Potapov et al., 2020). A set of regional forest disturbance detection models was specifically calibrated for Canada and applied annually from 1985 to 2020. The resulting disturbance layer shows the earliest year of forest disturbance. We did not use a forest extent mask for the stand-replacement disturbance detection product.

Partial forest disturbances were analyzed within the 2020 forest extent and outside the detected stand-replacement disturbances from 1985 to 2020. A partial disturbance indicates significant but incomplete removal of the tree canopy due to either natural or anthropogenic factors. These disturbances typically include (a) mixed pixels around stand-replacement disturbances, (b) burned areas with partial tree damage, (c) sparse tree mortality caused by wind or insect outbreaks, and (d) partial tree removal, such as selective logging, strip cuts, and shelterwood cuts. A set of regional partial forest disturbance detection models was calibrated specifically for Canada and applied annually from 1985 to 2020. The resulting partial disturbance layer shows the earliest year of forest disturbance.

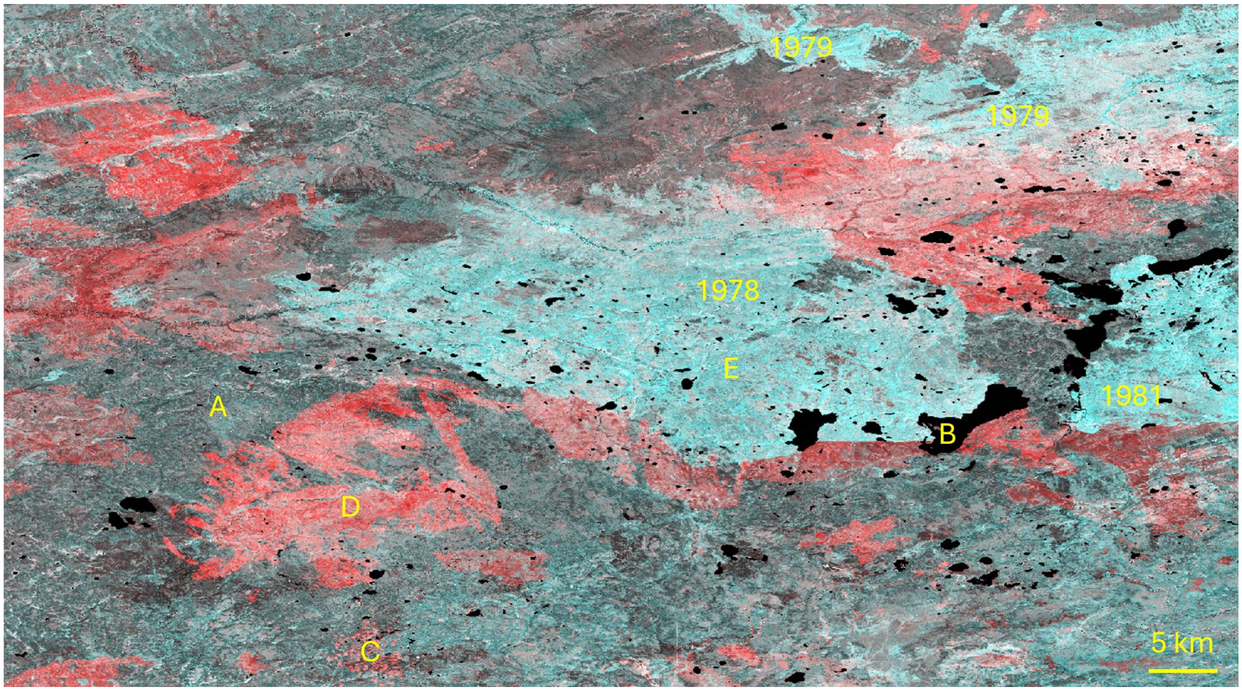


Figure 2. An example of Landsat SWIR band composite for the years 1988 and 2020 used to identify forest restoration areas. The sample area is in Northern Alberta. Image interpretation key: A – Structurally stable mature natural forest; B – Lake; C – Logged forest (1988-2020); D – burned forest (1988-2020); E – regenerating forest after a fire that occurred before 1988. The years of the fire events that led to forest regeneration are shown according to Amiro et al., (2001).

We analyzed forest areas affected by stand-replacing disturbances before 1985 by mapping forest regeneration that occurred after 1988, the first year with complete national cloud-free Landsat data. This analysis was done within the 2020 forest mask and outside areas affected by stand-replacement and partial disturbance after 1985. To visually identify forest regeneration areas, we used a combination of Landsat shortwave infrared reflectance (SWIR) bands from the 1988 and 2020 annual median reflectance composites (Fig. 2). We manually calibrated a set of regional models to map areas that experienced forest gain after 1988. A visual comparison of the resulting forest regeneration map with the Large Fire Database fire point data (Amiro et al., 2001) shows that fire events from the early 1980s are consistently mapped across the country, with a longer detection range (into the early 1970s) in the North and a shorter range in the South.

In addition to forest disturbance detected using our change detection method, we included in our analysis forest change and regeneration data produced by Natural Resources Canada and the University of British Columbia. We used Canadian forest fire data and timber harvest areas from 1985 to 2020 (Hermosilla et al., 2016), and forests 30 years and younger from the forest age database (Maltman et al., 2023).

All forest disturbance maps were combined to create a comprehensive disturbance layer for subsequent SSNF mapping. To reduce noise in the disturbance products (especially noticeable before 2000), we applied spatial filtering to the aggregated disturbance layer.

3.3. Built-up Lands, Infrastructure, and Intensive Land Use Data

Maps of built-up areas, mining sites, roads, power lines, and pipelines were collected from various open sources, including OpenStreetMap (OSM), Canadian national and provincial datasets, and ESA WorldCover 2021 (Zanaga et al., 2022). The data sources for intensive land use and infrastructure are summarized in Table 1. We exclusively used publicly available data. All vector objects (lines and polygons) were resampled to the 30 m/pixel raster grid. The 10 m/pixel resolution maps were resampled to the 30 m grid using the nearest neighbor method. The permanent cropland map, classified as an intensive land use category, was created by combining the year 2020 global cropland map (Potapov et al., 2021) with ESA WorldCover 2021.

Two separate layers were created: (a) **Infrastructure, built-up lands, and quarries**. This layer was used with a buffer to exclude mixed pixels and areas affected by edge effects.
(b) **Croplands**. This layer was not buffered for the final SSNF map production.

Table 1. Built-up lands, infrastructure, and intensive land use data sources

Land use type	Extent	Definition	Source or reference
Built-up lands	Canada	Land covered by buildings, roads, and other man-made structures.	ESA WorldCover 2021
Roads, railroads, power lines, pipelines	Canada	Linear infrastructure	OpenStreetMap contributors, 2024
Roads	Ontario	Linear infrastructure	Ontario Road Network and MNRF Road Segments(https://geohub.lio.gov.on.ca)
Pipelines	Alberta	Linear infrastructure	Alberta Energy Regulator (https://www.aer.ca)
Coal mines	Alberta	Quarries, polygon layer	Alberta Energy Regulator (https://www.aer.ca)
Roads, railroads	Canada	Linear infrastructure	National Road Network (https://open.canada.ca)
Cropland	Canada	Land covered with annual herbaceous crops in the year 2021.	ESA WorldCover 2021
Cropland	Canada	Land used for annual and perennial herbaceous crops.	The 2020 global cropland map, which was produced using the approach outlined by Potapov et al. (2021)

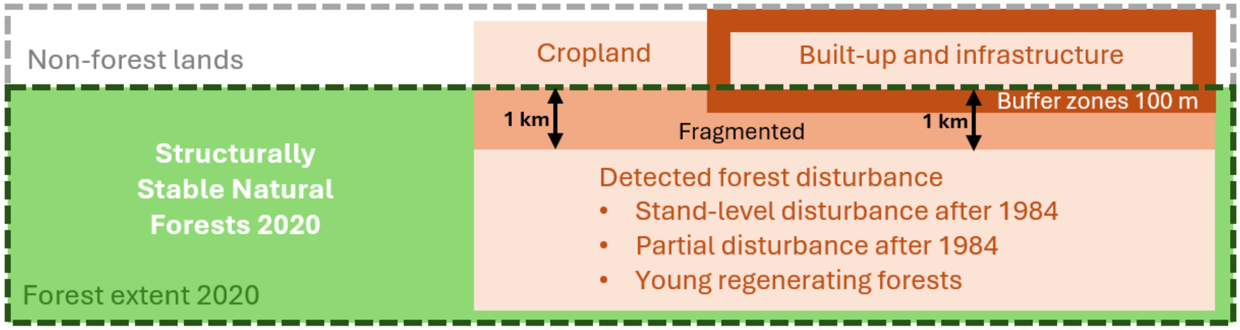


Figure 3. The SSNF candidate mapping logic. Detected disturbances and buffers from infrastructure are excluded from the forest extent map to create the SSNF layer. The fragmented elements with a width of less than 1 km are excluded if they are located between disturbed patches, croplands, or infrastructure.

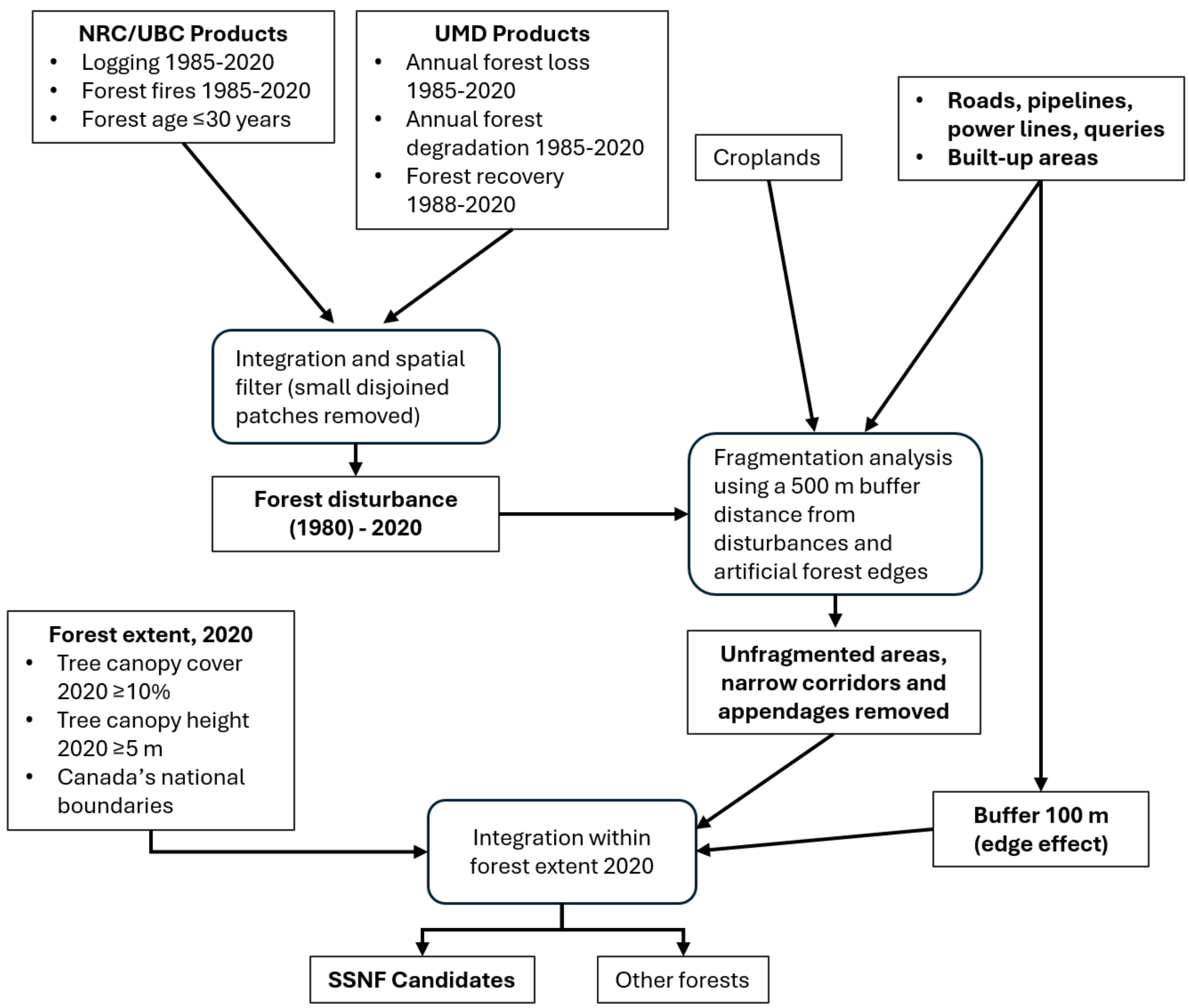


Figure 4. The SSNF candidate mapping flowchart.

3.4. Demonstration of the SSNF Mapping Algorithm

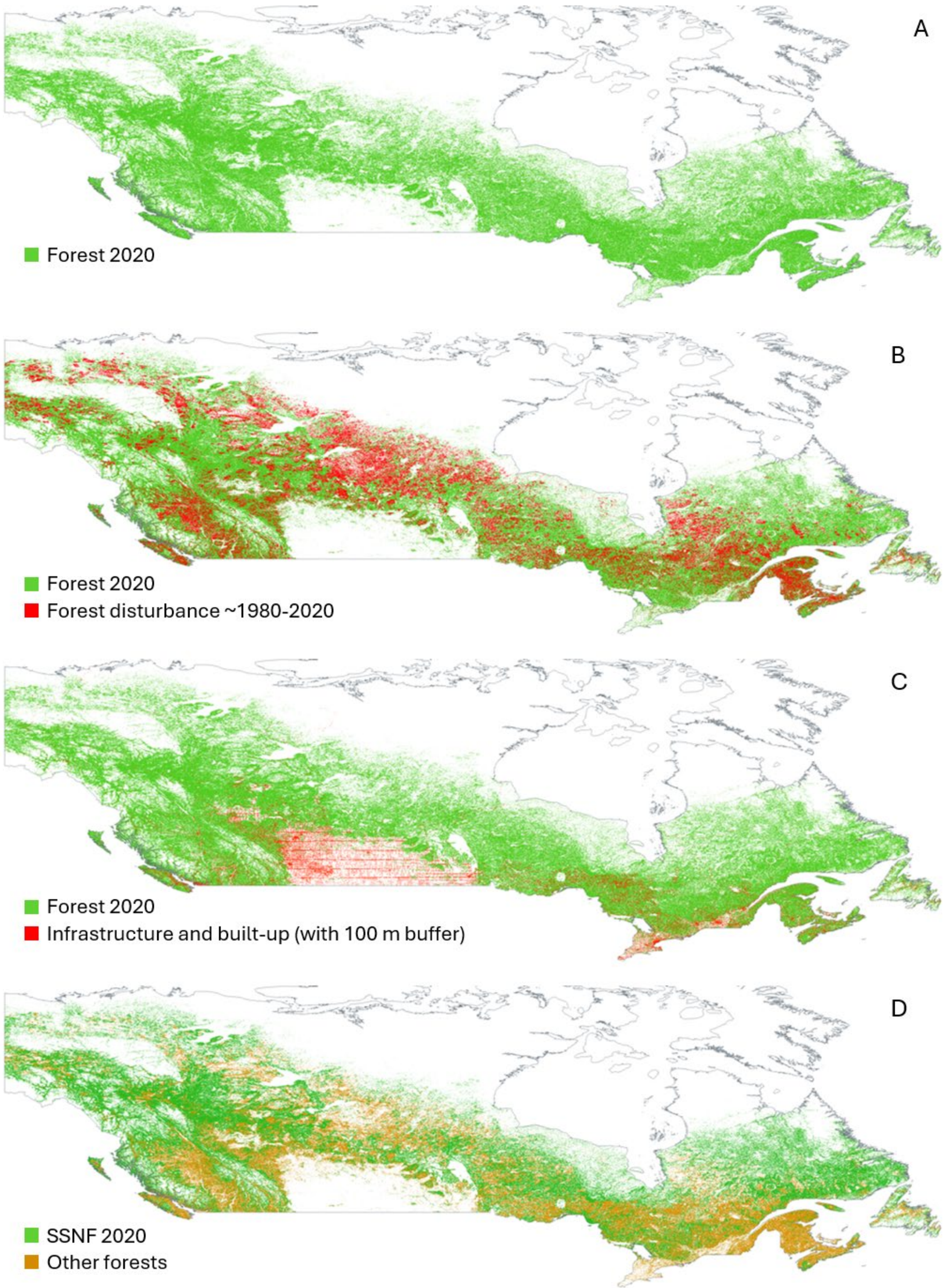
To create a demonstration SSNF candidate map, we used our thematic data and a set of criteria supported by literature on the effects of forest edges and infrastructure on wildlife and forest composition (Fig. 3 and 4).

The analysis was limited to the 2020 forest mask within Canada (Section 2.2), defined as areas with trees with canopy height ≥5 m and canopy cover ≥10 % at the Landsat pixel scale (Fig. 5A).

In the first stage of our analysis, we integrated all forest disturbance and recovery layers as described in Section 2.2 and applied spatial filtering to reduce false positive disturbance detections (Fig. 5B). The forest disturbance and recovery represent forests affected by stand-replacement and selective tree removal (both natural and anthropogenic) over the last ~40 years (although in the North the traces of 1970s forest fires may also be included due to slow tree regeneration). The forest disturbance layer was combined with croplands (intensive land use areas that fragment forests and create artificial edges with remaining forest patches) and the infrastructure, built-up, and quarries layer. We did not implement infrastructure buffering at this stage.

The integrated layer, which represents forest disturbance and artificial forest/non-forest edges, was used for fragmentation analysis to exclude narrow appendages and corridors that cannot support wildlife populations and migrations, as well as areas affected by adjacent infrastructure and land use. For caribou, Environment Canada (2011) suggested considering a 500 metre buffer around anthropogenic development. We excluded areas with a minimum width of 1000 m between disturbances, infrastructure, mining, built-up areas, and cropland. Our approach is similar to applying 500 metre buffer zones and excluding forest patches with no core area. To reduce artifacts within fragmented forest areas we used additional rules to exclude (a) narrow forest areas along lakes and wetlands fragmented by disturbances and roads and (b) areas with forest cores (outside the 500 metre buffer) smaller than 1 hectare.

The remaining undisturbed and unfragmented lands were overlaid with the 2020 forest map to identify SSNF candidate patches (Fig. 5D). The 100-metre buffer zones around built-up lands and infrastructure were also excluded. This buffer width is based on the estimated distance of edge influence on forest ecosystems (Harper et al., 2005; Franklin et al., 2021). We consider the remaining forest areas as candidate SSNF patches. While we did not apply a minimum patch size criterion, we suggest that a minimum patch size threshold should be used for the final map production.



Figire 5. SSNF mapping steps. A – Forest extent 2020 (Section 2.1). B – Forest disturbance (Section 2.2). C – Infrastructure and built-up lands (Section 2.3). D. SSNF candidates for the year 2020

4. Results

The forest extent, disturbance, and fragmentation layers developed in this project are provided as separate thematic layers, allowing for analysis and integration based on user-defined criteria. To demonstrate the use of these criteria, we created a preliminary national SSNF map for the year 2020. The map layers are provided at a spatial resolution of 30 metre/pixel in geographic coordinates. The data formats include raster map layers in GeoTIFF format and Google Earth Engine assets.

The total area of SSNF candidate patches is 209.6 million hectares, representing 59% of the total forest extent. The FAO reported that the primary forest area also represents 59% of the total forest extent (205 million hectares out of 347 million hectares of total forest area, FAO, 2020). Since our approach to identifying structurally stable forests differs significantly from the FAO reporting, we view this as a coincidence.

5. Discussion and Limitations

The SSNF candidate map represents the first step in the national data analysis. Our mapping algorithm, which relied exclusively on publicly available maps and satellite image classification, allowed us to exclude only the infrastructure objects found on public maps and recent forest disturbances from the last 40-50 years. Historical (before 1970s) forest use and disturbances cannot be identified using satellite data alone if the forest structure has been restored and represents a mature natural tree stand. Satellite imagery does not consistently allow for the identification of disturbance drivers, especially in areas where different disturbances, like logging and wildfires, overlap (e.g., within temperate forests). It is also challenging to identify drivers of pre-1985 disturbances, which are indicated only by the presence of broadleaf species and/or young trees.

Narrow logging roads, as well as abandoned roads and timber removal tracks, cannot be detected with moderate-resolution satellite data like Landsat. We recommend using visual image interpretation of very high-resolution historical imagery for manual mapping of disturbed, secondary, and planted forests within the SSNF candidate areas to create the primary forest map.

To guide future SSNF refinements, including potential manual image interpretation, we divided the national forest area into five regions based on different forest disturbance drivers, management histories, and landscape fragmentation (Fig. 6). The boundaries of these regions are informed by global ecoregions (Olson et al., 2001), logging tenures, infrastructure density, and disturbance patterns.

A. **Boreal forests outside the commercial exploitation zone**. The SSNF map in this region excludes burned areas since the mid-1970s, mining areas, and road buffers. This region requires minimal manual editing.
B. **Area of modern forest management**. This region is characterized by intensive logging operations and high road density within commercial forest zones. We excluded most forests affected by logging in the last 40-50 years, burned forests since around 1980, and areas fragmented by infrastructure. However, the remaining SSNF patches still include

fragmented forests (not all active and abandoned roads are represented in public datasets), forests impacted by historic harvesting, and even mature tree plantations.

C. **Oil and gas exploration and extraction region**. This region is heavily fragmented by roads, energy infrastructure, and seismic lines. However, public maps show only a fraction of these fragmentation sources. As a result, this region has the largest discrepancies between the Intact Forest Landscapes (Potapov et al., 2017) and SSNF maps (Fig. 7). Detailed manual corrections and/or the use of commercially available infrastructure maps are needed to exclude fragmented SSNF patches.

D. **Aspen parklands**. This region requires additional analysis and likely a different approach for SSNF mapping due to its unique forest type and dynamics.

E. **Forests with the longest history of management**. Most forests in this region have been historically impacted by management practices, including timber harvesting, tree planting, and land use changes (e.g., forests on historically abandoned agricultural lands). Manual SSNF analysis using high-resolution imagery may help detect some traces of historic management. However, traces of past management cannot be consistently identified without detailed historical analysis.

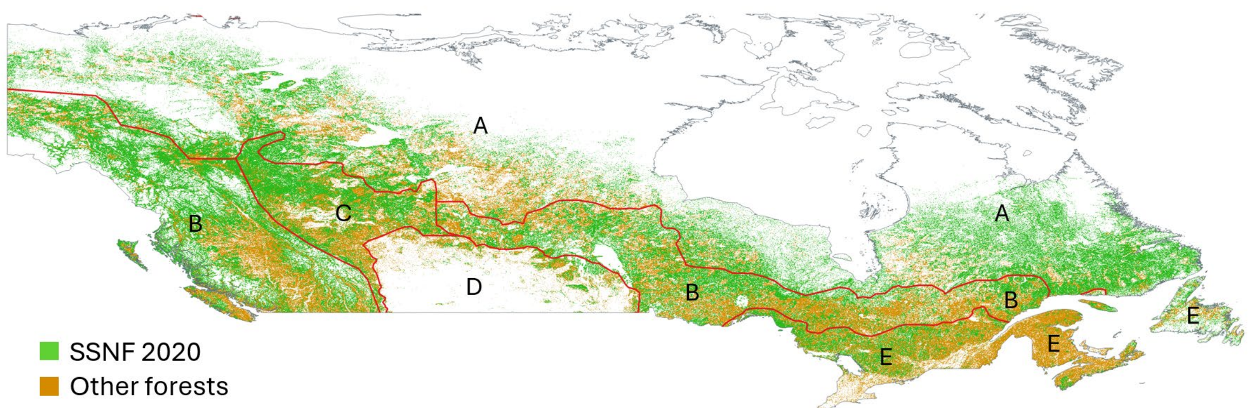


Figure 6. Regions of Canada by SSNF mapping issues. A – Boreal forests outside the commercial exploitation zone. B – Area of modern forest management. C – Oil and gas exploration and extraction region. D – Aspen parklands. E – Forests with the longest history of management.

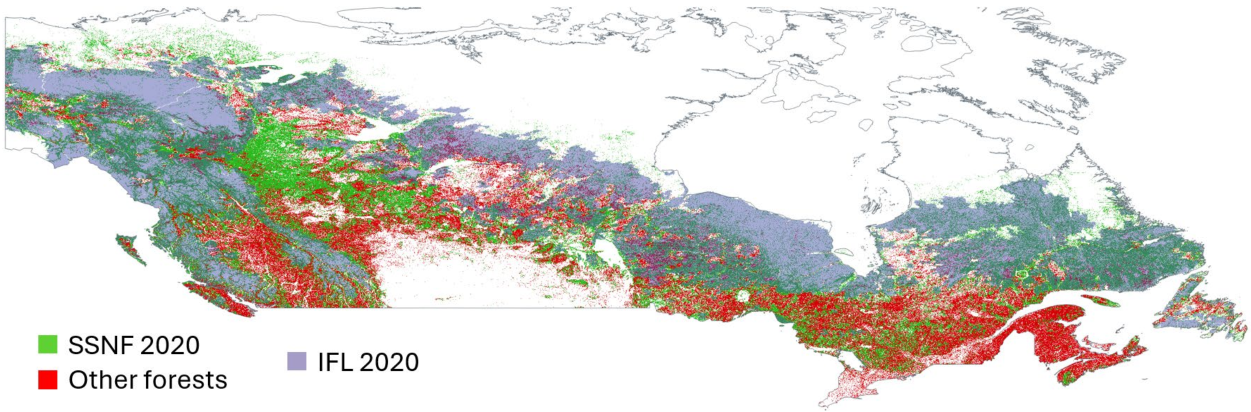


Figure 7. Overlay between SSNF candidate areas and IFL 2020.

6. Conclusion and Opportunities for Future Work

We presented a mapping framework that supports the identification of high conservation value forests and SSNF mapping. However, the SSNF map does not directly align with many accepted definitions of primary forest, including the definition recommended by Habitat (2024). Here, we discuss additional data analyses that may help progress primary forest mapping efforts in Canada.

6.1. SSNF map correction using visual interpretation

The SSNF mapping methodology does not account for historic logging and mature tree plantations that have shown no signs of tree canopy cover change in the past 40-50 years. Excluding these areas can only be done through visual analysis of Landsat and high-resolution imagery. National-scale mapping of such areas would require significant resources. To reduce workload and improve the efficiency of this analysis, it should be conducted only within the remaining candidate areas after excluding disturbed and fragmented forest patches. The number, size, and shape of these candidate patches will greatly affect the workload. We recommend using fragmentation criteria (e.g., minimum area, minimum width, or both) to exclude small and narrow fragments that have low conservation value.

6.2. Additional datasets supporting primary forest mapping

One key limitation of publicly accessible datasets is the lack of detailed maps of logging roads and oil and gas infrastructure (including seismic lines). Some data is available at the provincial or concession level, while other information comes from commercial vendors. Although these maps may still contain errors and gaps, they may greatly facilitate national fragmentation assessment and primary forest mapping.

The attribution of forest fires is another issue not addressed by the presented methodology. The existing global burned forest dataset (Tyukavina et al., 2022) and Canada's national burned areas (Hermosilla et al., 2016) can be used to attribute disturbance drivers. However, this approach has limitations: (a) it cannot attribute pre-1985 disturbances, and (b) correctly assigning disturbance drivers (e.g., partial tree canopy loss due to fire) will require manual editing and filtering.

7. Dataset Access and Metadata

All datasets created by our team are available online as raster GIS layers in two formats: GeoTIFF files and Google Earth Engine (GEE) assets. All data files share the same format:

Coordinate System: EPSG 4326 (WGS 1984)
Projection: Geographic coordinates
Corner Coordinates: Upper Left (-143.0005, 71.0005); Lower Right (-51.9995, 39.9995)
Pixel Size: 0.00025 × 0.00025 degrees
Image Size: 364004 × 124004 pixels
Data Format: 8-bit unsigned LZW-compressed.

7.1. Datasets:

Forest extent 2020
Pixel values: 1 – forest class defined as pixels with tree canopy height ≥5 m and canopy cover ≥10 %.
GeoTIFF: https://glad.umd.edu/users/Potapov/Canada_SSNF_2020/forest_2020.tif
GEE: https://code.earthengine.google.com/?asset=projects/ee-potapovpeter/assets/Canada_SSNF_2020/Forest

Forest disturbance ~1980-2020
Pixel values: 1 – forest disturbance class that includes tree canopy loss, degradation, and recovery detection between ~1980 (mid-1970s in the North) and 2020.
GeoTIFF: https://glad.umd.edu/users/Potapov/Canada_SSNF_2020/disturbance_2020.tif
GEE: https://code.earthengine.google.com/?asset=projects/ee-potapovpeter/assets/Canada_SSNF_2020/Disturbance

Infrastructure, built-up and quarries
Pixel values: 1 – rasterized roads, railroads, power lines, pipelines, quarries, and built-up lands from public data sources; 2 – 100-m buffer around all infrastructure and built-up pixels.
GeoTIFF: https://glad.umd.edu/users/Potapov/Canada_SSNF_2020/infrastructure_2020.tif
GEE: https://code.earthengine.google.com/?asset=projects/ee-potapovpeter/assets/Canada_SSNF_2020/Infrastructure

SSNF 2020
Pixel values: 1 – Other forests; 2 – SSNF 2020.
GeoTIFF: https://glad.umd.edu/users/Potapov/Canada_SSNF_2020/ssnf_2020.tif
GEE: https://code.earthengine.google.com/?asset=projects/ee-potapovpeter/assets/Canada_SSNF_2020/SSNF

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