



RESEARCH TO LOCATE AND COMPARE SPATIAL DATASETS FOR MAPPING PRIMARY FORESTS ACROSS CANADA

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Disclaimer

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The author acknowledges that the work for this project references the unceded ancestral lands of Indigenous Peoples across Canada. At UBC Vancouver, we are on the traditional, ancestral, and unceded territory of the hə́nq̓əmiṇə́m speaking xʷməθkʷə́yəm (Musqueam) people. We commit to learning from Indigenous communities and supporting truth, reconciliation, and respectful relationships.

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Executive Summary

This study presents a detailed, multi-step geospatial workflow designed to map Canada's primary forests, defined as *forests of any age composed of naturally regenerated native species, undergoing natural ecological processes, and free from recent or major anthropogenic disturbance apart from traditional land use*. Using a robust set of national, provincial, and regional datasets, the project aimed to produce the framework for a spatially accurate and thematically comprehensive national map of primary forests.

The workflow was divided into three components. Part one established the baseline forest extent using Hansen et al. (2013)'s global forest cover dataset (2000–2023, 30 m), refined to exclude low-stature trees (<5 m) and areas impacted by harvest or agriculture. Multiple harvesting datasets, including Landsat-driven disturbance records, forest inventories, and provincial databases, were spatially standardized and masked to derive a core natural forest layer.

Part two identified and removed major anthropogenic disturbances. This included masking areas of documented forest loss, resampled human footprint indices (originally 300 m, downscaled to 30 m), urban expansion, hydroelectric and mining operations, and extensive linear infrastructures such as roads, pipelines, and power lines. Custom buffer distances were applied to ensure ecological impact zones were excluded. Subsequently, permanent water bodies (lakes, wetlands, rivers, etc.) were masked, producing a refined layer of ecologically intact, naturally regenerated forests.

Part three classified the remaining forest areas into three categories based on patch size and connectivity: (i) Primary Forest Fragments (<1,000 ha or corridors <500 m wide), (ii) Primary Forests (1,000–50,000 ha), and (iii) Primary Forest Landscapes (>50,000 ha).

The identified workflow and datasets provide a framework for mapping the spatial distribution and extent of Canada's remaining primary forests. While numerous data strengths were identified, including high spatial resolution, rich attribute content, and strong temporal depth (most of the data span a long historical period), significant data gaps were also evident. These included incomplete harvesting records, unclassified fire data, and limited information on reforestation, traditional land use, and natural disturbances like insects or windthrow.

Technical limitations, such as inconsistent projections, coarse-resolution layers, and computational challenges due to large datasets, were addressed using advanced geospatial methods, including reprojection, resampling, rasterization, and data harmonization. Despite these efforts, some precision limitations remain, particularly regarding buffer applications and

data conditions. Results may vary depending on buffer selection, data availability, and the spatial and temporal extent of data.

Opportunities for future research include improving fire cause attribution, integrating more up-to-date or finer-resolution datasets, expanding traditional land use layers, and applying machine learning techniques to refine disturbance detection. This framework can serve as a foundation for ongoing forest conservation, policy support, and ecological assessment across Canada.

Background

Primary forests cover an estimated 59% of Canada's forest land (FAO, 2020), yet they continue to face mounting threats from logging, infrastructure development, and climate-driven disturbances such as wildfires. Accurate and detailed mapping is crucial for effective conservation planning, informed sustainable land use decisions, and meeting biodiversity and climate change commitments. However, Canada lacks a cohesive spatial dataset of primary forests across national, provincial, and regional levels – a gap that limits effective forest stewardship.

To address this gap, WWF-Canada is working toward a primary forest map for Canada, guided by the operational definition and methodology proposed by Habitat (2024). Stemming from an examination of the literature, Habitat proposed to define primary forests as “forest of any age class, composed of naturally regenerated native species, undergoing natural ecological processes, that have not been impacted by recent or major anthropogenic disturbances or usage other than traditional land use.”

WWF-Canada has undertaken the task of developing a national primary forest spatial dataset to address Canada's longstanding gap in consistent forest classification and mapping. The effort began with an initial review of publicly available datasets from federal, provincial, academic, and independent sources by Habitat. WWF-Canada identified and evaluated those with the potential to support a nationwide primary forest mapping initiative. This initial data screening included geospatial layers relevant to forest structure, disturbance history, ecological characteristics, and land use designations. Following this review, WWF-Canada gathered the datasets and initiated a first-round mapping effort that applied the Habitat (2024) primary forest definition and workflow as a methodological foundation.

Project Scope

Building on these initial phases of work, the UBC Sustainability Scholar has advanced to the next phase of developing a refined and comprehensive primary forest dataset and workflow. This phase involved the systematic identification and compilation of additional spatial datasets at the regional, provincial, and national levels. Data sources included government agencies, non-governmental organizations, and academic platforms, with a focus on broad geographic coverage and data relevance. Key datasets included high-resolution layers related to forest cover, anthropogenic disturbances (e.g., logging, roads, mining, etc.), and cultural or ecological constraints that affect forest continuity.

The UBC Sustainability Scholar processed and organized these datasets into thematic layers, including forest cover, disturbance history, human footprints, forest loss, linear features (i.e., roads, pipelines, powerlines), hydrology, resource and mining disturbances, and ecological structure (i.e., plantations). These were used to develop a comprehensive primary forest dataset across Canada.

As part of this process, an extensive data gap assessment was conducted to identify key limitations in spatial coverage, update frequency, regional consistency, etc. In addition, numerous recommendations were proposed as potential solutions to address these data deficiencies, including integrating scientific and Indigenous knowledge, enhancing data standardization, and improving the timeliness and resolution of critical datasets. These recommendations were employed to build a multi-tiered framework to support primary forest classification.

This methodology has been applied to the vetted datasets to produce the framework for an updated national primary forest map, building on the initial work by WWF-Canada. The result is a more accurate and policy-relevant dataset to inform conservation, planning, and climate resilience efforts, which can contribute to informing various mapping and conservation efforts related to primary forests in Canada.

Materials and Methods

This section outlines the data sources, processing steps, and methodological workflow used to develop a refined primary forest dataset for Canada. A diverse range of spatial datasets, spanning multiple formats and spatial scales, was compiled and analyzed to support the mapping process. These datasets were systematically organized and processed to ensure consistency, accuracy, and alignment with the updated definition and criteria for identifying primary forests across the Canadian landscape.

Data Sources and Spatial Coverage

Several key categories of publicly available spatial datasets were utilized as foundational inputs for primary forest mapping, comprising over 60 spatial datasets on forest cover, forest loss, harvesting activities, human footprint, infrastructural disturbances, etc., which were subsequently organized into nine thematic groups. The datasets were obtained in both raster and vector formats, varying in spatial resolution and scale across provincial and national levels. Raster data resolutions ranged from 30 m to 300 m. Most notably, the Canadian Human Footprint Index was originally at 300 m and subsequently resampled to 30 m resolution. Other raster layers, such

as forest cover and forest loss, were available at 30 m resolution. Vector datasets had spatial scales ranging from 1:5,000 to 1:50,000 and were rasterized to 30 m resolution to ensure consistency in processing.

Temporal coverage also varied across datasets, reflecting differences in data availability and collection periods. For example, forest cover and loss data span from 2000 to 2024, while harvesting records cover the period from 1985 to 2020. Despite the diversity in formats and timeframes, each data category contributes multiple raster and vector inputs, enhancing the accuracy and resolution of the final primary forest map. Table 1 lists the main dataset categories along with brief descriptions.

Table 1: List of available datasets for primary forest mapping across Canada.

DATA TYPE	DATA LIST	BRIEF DESCRIPTIONS
Forest cover ^[1-2]	- Global forest coverage - Satellite-based forest inventory	Forest cover data was considered for canopy closure, tree heights, and forest losses over the past few decades.
Forest loss ^[1]	Global forest loss	This dataset analyzes global forest loss since 2000 using Landsat-derived data at a 30 m spatial resolution.
Harvesting ^[3-22]	- Vegetation inventory index - Timber harvesting - Clear-cutting - Crown forest management - Stand forest improvement - Logging - Agricultural activities	This dataset included various harvesting, forest management, agricultural lands, etc., over the past few decades. Raster data resolution is 30 m, along with provincial-level detailed polygon datasets. Harvesting is considered a major disturbance for primary forest mapping.
Human footprint ^[23-24]	- Human footprint index - Human modification index	Human footprint represents human disturbance through anthropogenic activities. This data has a relatively low spatial resolution of 300 m, whereas most datasets have a resolution of 30 m.
Waterbodies ^[25-26]	- Wetlands - Lakes, rivers, and other waterbodies	Different types of hydrological features are identified through raster analysis and polygon data at the provincial level.
Deforestation/ Reforestation ^[27-28]	- Plantation - Reforestation	Deforestation and plantations are identified based on historical provincial databases.

DATA TYPE	DATA LIST	BRIEF DESCRIPTIONS
Fire disturbances ^[29-39]	• Wildfires • Forest burn index • Burn area composition	Fire databases are based on raster indices and provincial mapping over time.
Natural disturbances ^[40-44]	• Insects and Diseases	Limited insect and disease datasets were identified.
Other disturbances ^[45-60]	• Mining • Forest roads • Roads and highways • Towns and urban zones • Hydroelectric development (dams, reservoirs, etc.) • Pipelines, electricity lines, etc.	These datasets are extensive and mostly based on buffer analysis and build-up indices. Several buffer values are used depending on the disturbance category. The buffer value for different datasets is- open-pit mining- 14 km; mining- 2 km; major roads- 2 km; roads, forest roads, pipelines & electricity lines- 1 km; towns and urban zones- 9 km, and dams & major infrastructure 14 km.

Note: Footnote numbers correspond to the representative data sources and associated data acquisition guidelines in Appendix A.

Methodology

This section outlines the methodological framework used to produce a 30 m-resolution draft map of primary forests across Canada. The process involved the acquisition, evaluation, and integration of diverse geospatial datasets, followed by spatial analyses tailored to the Canadian ecological and disturbance context. The workflow included five major components: data acquisition and categorization (see preceding section), data gap assessment, preprocessing and standardization, refinement of mapping criteria, and development of a spatial workflow to produce a draft primary forest map.

Data Gap Assessment

A comprehensive data gap assessment was conducted to evaluate the suitability and completeness of all spatial datasets used in the primary forest mapping process. This assessment aimed to ensure the reliability, consistency, and national applicability of the data inputs. Each dataset was systematically reviewed across multiple dimensions, including spatial extent, temporal coverage, update frequency, projection, and coordinate system, spatial resolution, map scale, and positional and thematic accuracy.

Special attention was given to identifying regional inconsistencies, such as uneven data availability across provinces or territories, and temporal lags that might compromise mapping precision. For example, certain harvesting records or linear disturbance datasets were only available up to specific years or covered limited geographic regions. Additionally, variations in data formats (raster vs. vector) and scales required technical harmonization to facilitate their integration into a national workflow.

The objectives of this gap assessment were not only to highlight limitations but also to propose practical solutions to address deficiencies, such as resampling or upscaling lower-resolution datasets (e.g., the 300 m Canadian Human Footprint Index) to match the target 30 m spatial resolution, recommending future data acquisitions or methodological updates to improve completeness in underrepresented areas.

The data gap assessment informed and guided the development of a robust primary forest map across Canada. Despite several challenges, including missing harvesting data, unclassified disturbances, and inconsistent resolutions, these issues were addressed through systematic pre-processing, resampling, reprojection, and the integration of supplementary datasets.

Contemporary geospatial tools and techniques were applied to overcome technical constraints and harmonize data from multiple sources. As a result, a high-resolution, methodologically sound, and spatially consistent primary forest dataset was successfully created, reflecting the best available information. This foundation supports transparent, science-based decision-making for conservation and forest management across Canadian landscapes.

Preprocessing and Standardization

All datasets underwent extensive preprocessing to ensure integration and analytical consistency within the workflow. A suite of advanced geospatial techniques were applied, including resolution resampling, projection standardization, dataset harmonization, spatial transformations, etc. These procedures were critical for minimizing processing errors, enhancing spatial accuracy, and enabling the production of a reliable primary forest map for Canada.

- **Standardize Resolution and Projections:** Datasets were resampled and reprojected to a consistent spatial resolution (e.g., 30 m) and common coordinate system to ensure spatial alignment and integration.
- **Pre-processing and Data Cleaning:** Inconsistent datasets were filtered, fragmented datasets (e.g., harvesting) were harmonized, and errors were corrected to improve consistency across jurisdictions.

- Downscale Coarse Layers: Spatial interpolation, resample smoothing techniques, or machine learning models were applied to enhance low-resolution datasets (i.e., convert 300 m Human Footprint Index to 30 m).
- Buffer Linear and Point Features: Buffers were generated around roads, railways, mining areas, urban centers, etc., to capture zones of influence and support spatial interaction analysis.
- Rasterized Vector Layers: Vector data were converted into 30 m raster format, enabling integration with other raster datasets and supporting consistent spatial analysis.

Mapping Criteria

Using the operational definition of primary forests proposed by Habitat (2024) and incorporating feedback from stakeholder workshops, WWF-Canada applied consistent spatial rules for classification. A primary forest was defined as an area dominated by native vegetation taller than 5 m, naturally regenerated, and free from recent or major anthropogenic disturbance.

Workflow Development

Habitat's (2024) workflow was modified to sequentially integrate and analyze spatial layers. This included stepwise masking of disturbance features, logical overlay operations, spatial filtering, and patch classification. The workflow was built for flexibility and regional adaptability, enabling future updates and broader applications.

Technical Infrastructure and Tools

To manage and process the extensive dataset efficiently, analysis was conducted using high-performance computing infrastructure, including a custom-built machine with 256 GB RAM and an Intel® Xeon® Gold 6142 CPU. Software tools included ArcGIS Pro, ArcMap, QGIS, Google Earth Engine, RStudio, and Python, ensuring a scalable, accurate, and reproducible workflow.

Results and Discussion

Final Mapping Workflow

One of the core objectives of this research was to enhance and update Habitat's (2024) flowchart used for mapping primary forests in Canada. The updated workflow provides a more systematic and transparent approach, aligning with Habitat's proposed 2024 definition. The goal of this flowchart is to visualize a systematic approach for mapping Canada's primary forests, using Habitat's proposed definition of *forests of any age class, composed of naturally regenerated native species, undergoing natural ecological processes, that have not been impacted by recent or*

major anthropogenic disturbances or usage other than traditional land use (2024). To enhance clarity and improve methodological transparency, the workflow was divided into three main parts.

The first part (Fig. 1) focuses on defining the baseline forest cover and eliminating major anthropogenic disturbances to identify areas of naturally regenerated forest. The Global Forest Change dataset by Hansen et al. (2013) was used as the foundational source, providing annual, Landsat-based forest cover data from 2000 to 2023 at a 30 m spatial resolution. To ensure ecological accuracy, only areas with canopy height exceeding 5 m were retained, effectively excluding non-forest elements such as shrublands and young plantations.

Following this, a comprehensive suite of forest disturbance datasets was compiled and integrated, including Landsat-driven forest harvest disturbances from 1985 to 2020 (Hermosilla et al., 2016), vegetation inventory-based forest (AVI, 2022) and agricultural activity layers (Conservation Biology Institute, 2020; Hansen et al., 2013), and detailed provincial and regional-level vector data on clear-cutting (Consolidated Cutblocks, 2023; FTA 4.0, 2025; Geomatics Yukon, 2021; Harvest Blocks, 2023, etc.) and logging operations (Conservation Biology Institute, 2020; Hansen et al., 2013). These diverse datasets were standardized through a harmonized pre-processing pipeline involving reprojection into a common coordinate system and resampling to 30 m resolution. The unified disturbance layers were then overlaid on the forest cover map, and disturbed areas were systematically masked out. The result of this process is a refined forest cover layer representing undisturbed, naturally regenerated forest ecosystems, which serves as a critical baseline for the next phases of primary forest identification.

The second part of the workflow (Fig. 2) focuses on identifying and eliminating major anthropogenic disturbances and excluding hydrological features to refine the forest layer derived from Part 1, ensuring strict alignment with the definition of primary forests. This stage integrates multiple datasets indicative of human-induced impacts on forested landscapes. The Global Forest Change dataset by Hansen et al. (2013) was utilized to account for forest loss between 2000 and 2023 at a 30-meter resolution. In parallel, the Canadian Human Footprint Index (Conservation Biology Institute, 2020), originally available at a coarse 300 m resolution, was downsampled to 30 m using spatial resampling techniques to align with the analytical framework. These layers were then masked from the previously derived naturally regenerated forest cover, producing a forest extent free from recent forest loss and large-scale human disturbance.

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(NRC, 2019c), were incorporated, with buffer distances summarized in Table 2. These features were standardized to 30 m resolution and masked from the forest extent.

Table 2: Applied buffer radius (area) in linear and non-linear features.

FEATURES	BUFFER (KM)
Roads	1
Major roads, pipelines, railways, electricity transmission corridors, and mines	2
Towns and urban zones	9
Dams	14
Major infrastructure	14
Open-pit mining	14

Finally, the exclusion of hydrological features was performed to isolate strictly terrestrial forest areas. Lakes, rivers, wetlands, ponds, and other water bodies (NRC, 2023d; Wetlands, 2023) were incorporated from high-resolution hydrographic datasets, rasterized to 30 m, and subtracted from the previously filtered forest layer. This final masking step delivered a forest extent composed exclusively of ecologically intact, naturally regenerated, and undisturbed terrestrial forest ecosystems (Xiao, 2024; Xiao et al., 2024), thus conforming to the proposed operational definition of primary forests in Canada. This output represents the most refined product in the workflow and serves as a critical input for statistical analysis, classification, and spatial pattern assessments in subsequent stages.

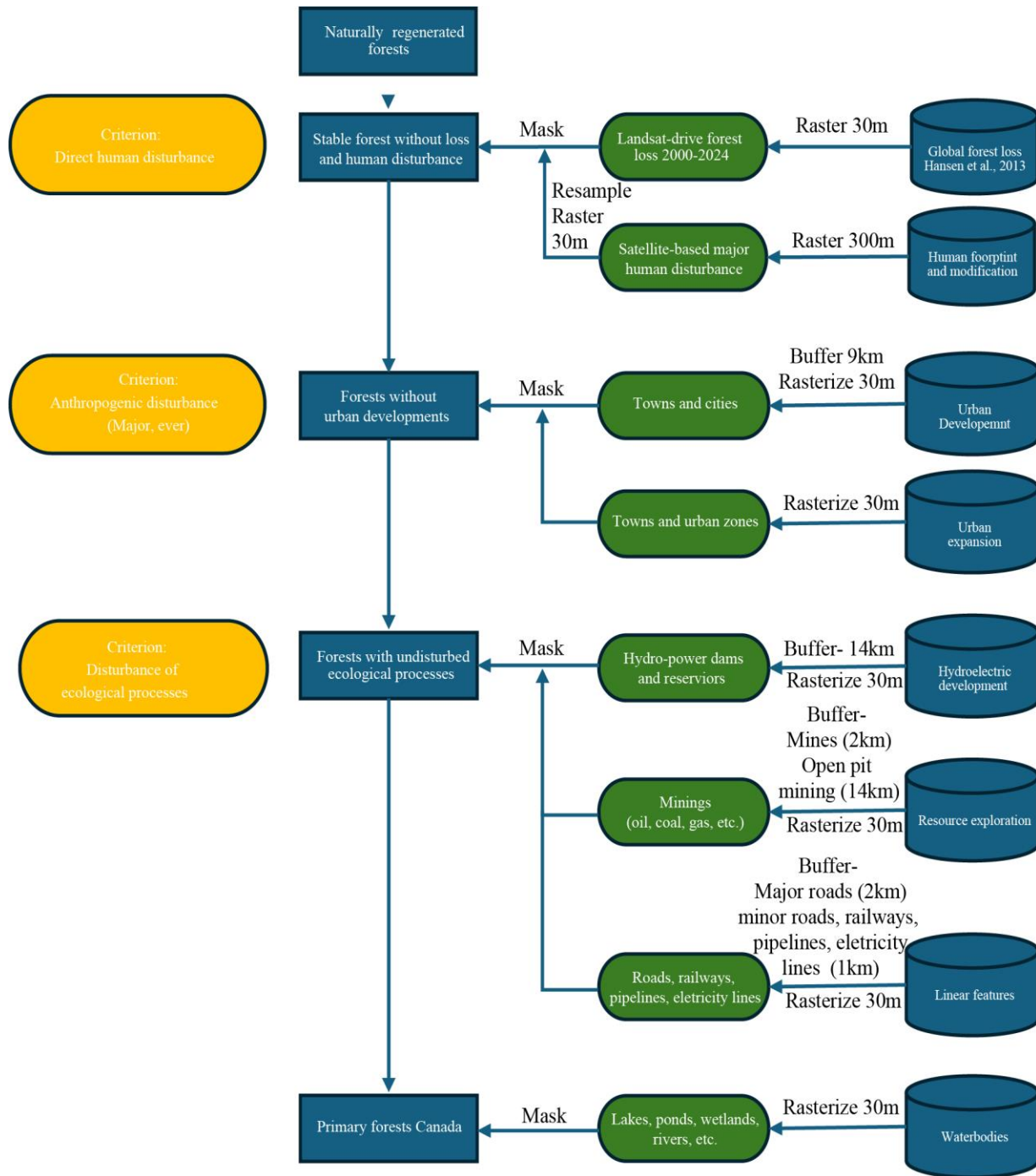


Figure 2: Workflow for primary forest mapping across Canada (Part 2- major disturbance)

Part 3 (Fig. 3) of the workflow involved the spatial classification of the derived primary forest map based on patch size, to reflect varying degrees of ecological integrity and landscape-scale continuity. The contiguous forest patches identified in the previous step were analyzed and

categorized into three distinct classes according to their total area and spatial configuration. These classes are as follows:

- i. Primary Forest Fragments, defined as patches smaller than 1,000 ha or linear corridors narrower than 500 m, which often exhibit edge effects and limited core habitat;
- ii. Primary Forests, comprising patches ranging from 1,000 to 50,000 ha, which typically retain ecological functionality while potentially being influenced by surrounding land use; and
- iii. Primary Forest Landscapes, defined as extensive, uninterrupted forest areas exceeding 50,000 ha, which represent the highest degree of ecological integrity and are most capable of supporting long-term natural processes and biodiversity at scale.

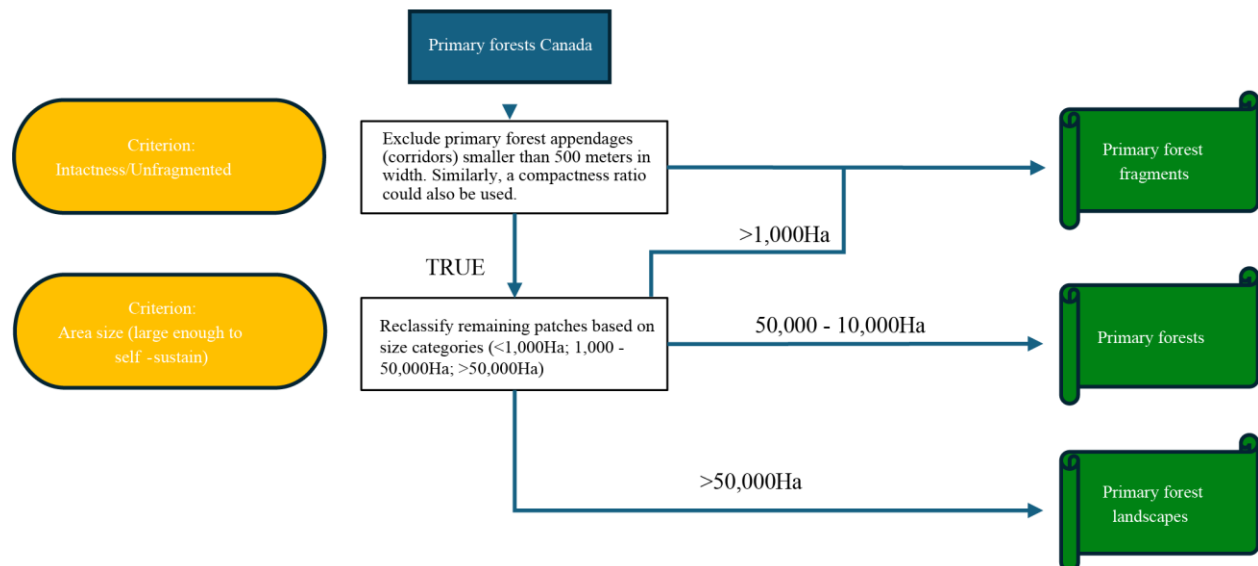


Figure 3: Workflow for primary forest mapping across Canada (Part 3- classification)

This classification facilitates further analysis and prioritization for conservation planning, ecological assessments, and policymaking aimed at protecting remaining primary forests in Canada.

Data Strengths, Addressing Data Gaps, and Remaining Limitations

The assessment revealed strong national datasets for several variables, providing consistent spatial coverage and thematic reliability. However, notable gaps were identified, including incomplete harvesting data in some provinces, coarser-resolution human disturbance layers, and limited temporal coverage of natural disturbance data. These deficiencies contributed to regional

inconsistencies and reduced precision in certain areas, underscoring the need for improved data acquisition and harmonization.

Data Strengths

The datasets used for primary forest mapping in Canada offer several notable strengths that support robust spatial analysis and classification. These strengths span spatial resolution, data reliability, temporal coverage, and interoperability, providing a solid foundation for accurate mapping. Key advantages of the available datasets are summarized below:

- **Appropriate Spatial Resolution:** Most raster datasets are at 30 m resolution, offering detailed spatial information suitable for national and regional level analysis.
- **Rich Attribute Information:** Many datasets include high spatial resolution attribute data, enhancing their analytical utility for classification and assessment.
- **Interoperable Formats:** Data is typically available in widely used formats (e.g., TIFF, shapefile, KML, GDB), compatible with mainstream GIS platforms such as ArcGIS, QGIS, etc.
- **Data Availability:** Most of these datasets are freely available, supporting open science and transparency. However, datasets from published sources were also included, with some data only available upon request, such as harvesting data from Ontario.

Addressing Data Gaps

To address the identified data gaps, a range of mitigation strategies were implemented throughout the mapping process. These approaches, such as dataset cross-validation, spatial enhancement, and integration of supplementary sources, were actively used to improve data quality, fill out missing information, and ensure a more accurate and comprehensive primary forest map.

- **Harvesting Data:** National and provincial datasets were cross-referenced through overlay and comparative analysis to identify and fill gaps, validate harvesting extent, and improve accuracy.
- **Human Disturbance Data:** Available data were processed using buffer analyses and resampling techniques (i.e., pan-sharp smoothing) to achieve 30 m spatial resolution, and geostatistical methods were applied to validate and refine index-based layers.
- **Natural Disturbance Data:** Datasets on pathogens, insect outbreaks, and windthrow were not available and were therefore excluded from the mapping process.
- **Forest Fire Data:** All forest fire events were treated as part of natural forest dynamics and excluded from anthropogenic disturbance mapping. While fires can be caused by human

activities and climate change may be increasing their frequency and severity, fire is still predominantly a natural process in most of Canada's forests. Current evidence is insufficient to classify fires as anthropogenic disturbances, so they were considered natural for this study.

- **Reforestation and Plantation Data:** National datasets were compared with available provincial records to identify discrepancies, and higher-accuracy data were prioritized to ensure a robust primary forest dataset.

Limitations in Available Datasets

Despite the mitigation measures applied to identified data gaps, comprehensive data preprocessing, and integration of multiple datasets, the primary forest mapping process in Canada is subject to several limitations that may affect the accuracy, completeness, and reproducibility of the final dataset. These limitations arise from both the availability and quality of spatial datasets, as well as technical and computational challenges inherent to large-scale geospatial analysis. Recognizing these constraints is critical for interpreting results and applying the datasets in conservation, policy, or land management contexts.

- **Data Resolution and Processing Artifacts:** Many datasets required reprojection, rasterization, or downscaling (e.g., converting 300 m coarse-resolution raster layers to 30 m) to achieve a consistent spatial resolution. These transformations can introduce spatial artifacts and reduce precision, particularly at ecotonal boundaries, feature-dense regions, or areas with heterogeneous landscapes. Resampling and rasterizing vector features, while necessary for alignment, can further propagate minor inaccuracies.
- **Limited Harvesting Data:** Detailed and provincial-level spatial data on harvesting, clear-cutting, and industrial logging activities are unavailable for Manitoba, Saskatchewan, and Prince Edward Island. In addition, the temporal coverage for provincial-level harvesting data is limited for New Brunswick (since 2021), British Columbia (since 2007), Ontario (since 2002 and 2005), and Nova Scotia (since 2016).
- **Inadequate Human Disturbance Data:** National-level datasets on mining, roads, dams, pipelines, electricity lines, etc., often lack fine detail. The Canadian Human Footprint Index, while available, is modeled and at a coarse 300 m spatial resolution across Canada. Poley et al. (2022) provide high-quality national road data compiled from multiple regional, provincial, and national-scale datasets. However, detailed electricity data remain unavailable.

- **Unavailable Natural Disturbance Data:** Comprehensive national or provincial datasets for pathogens, insect outbreaks, and windthrow are largely unavailable, except for some insect data from New Brunswick and Ontario.
- **Unclassified Fire Causes:** Fire datasets exist at the national level and for some provinces, such as Manitoba and Prince Edward Island, but the causes are not classified or differentiated between natural and human-induced events. Alberta is an exception in terms of classified forest fire data, but the rest of the country lacks this distinction.
- **Limited Traditional Land Use Layers:** Publicly available Indigenous traditional land use datasets are extremely sparse. Most records are point-based, identifying community locations without spatial extent, which limits the ability to incorporate traditional land use into primary forest mapping.
- **Reforestation and Plantation Data:** Reforestation data are only available provincially for New Brunswick. A national-level plantation dataset by Xiao et al. (2024) is available, derived from Landsat imagery and may contain notable inaccuracies. In particular, planted trees can exhibit growth patterns, such as height, canopy cover, and overall structure, that closely resemble primary forest. These similarities can also be influenced by soil conditions and other environmental factors, making it difficult to reliably distinguish plantations from forests.
- **Buffering Imprecision:** The use of different buffer distances around anthropogenic features (e.g., roads, dams, urban zones) may either fail to capture or overcapture nuanced ecological gradients or species-specific sensitivities.
- **Data Integration Challenges:** Harmonizing datasets from various sources with inconsistent projections, scales, and formats can introduce alignment issues and complicate spatial accuracy.
- **Computational Constraints:** Processing over 60 high-resolution layers required substantial computational and storage resources, including a high-performance workstation (256 GB RAM, Intel Xeon Gold CPU). Iterative spatial analyses, resampling, and masking at 30 m resolution across a national extent were time-intensive, and substantial disk space was needed to manage raw, intermediate, and processed datasets. These requirements may limit reproducibility on standard computing systems or projects with restricted storage capacity.
- **Temporal Gaps in Updates:** Some datasets used in the workflow are not updated annually, which may limit the temporal relevance of the map and obscure recent land-use changes or disturbances.

These limitations, while non-trivial, are common in large-scale environmental mapping efforts and are important to consider when interpreting the results or applying the dataset to policy, conservation, or land management decision-making.

Draft Primary Forest Map¹

The final output of the workflow is a draft map delineating the distribution of primary forests across Canada at a 30 m resolution. Subsequent work could focus on refining and finalizing this draft map.

Opportunities for Future Research

Future research can build on this work by addressing current data limitations and incorporating new analytical approaches. Expanding datasets, improving disturbance classification, and integrating Indigenous knowledge and climate modeling offer valuable opportunities to enhance the accuracy, relevance, and ecological depth of primary forest mapping in Canada. The following are a few potential opportunities for future research, though the list is not exhaustive.

- **Addition of New Data:** Continuous engagement with governmental agencies, NGOs, Indigenous organizations, and academic institutions can support the integration of newly released or underutilized datasets, thereby improving spatial completeness and thematic accuracy.
- **Indigenous Land Use Mapping:** Collaborating with Indigenous communities to incorporate traditional knowledge and spatial data could help fill critical gaps in traditional land use and cultural landscape mapping, enriching both the ecological and ethical value of the dataset.
- **Temporal Dynamics of Primary Forests:** Future studies could develop time-series models to track transitions in primary forest status and identify areas at risk of disturbance or undergoing natural regeneration.
- **Machine Learning for Disturbance Detection:** Incorporating artificial intelligence and machine learning methods could enhance the detection and classification of subtle or

¹ The broader primary forest mapping initiative and its associated GIS workflows are still under refinement through ongoing expert review. Prototype maps will be released at a later stage as the project progresses. For additional information, please contact Devon Earl, WWF-Canada, at dearl@wwfcanada.org.

small-scale disturbances (e.g., selective logging, edge effects), which are often missed in current datasets.

- **Ecosystem Integrity Indexing:** Building on the mapped primary forests, researchers could explore creating ecosystem integrity indices that incorporate biodiversity, carbon storage, habitat connectivity, and resilience metrics.
- **Validation and Ground Truthing:** Expanding field-based validation efforts, possibly through citizen science or UAV surveys, would significantly improve the confidence in remotely sensed classifications and improve model calibration.
- **Forest Connectivity and Fragmentation Analysis:** Investigating the structural and functional connectivity of primary forest landscapes using graph theory or circuit models can offer deeper insights into ecological resilience and conservation priorities.
- **Climate Change Overlay Modeling:** Examining how climate change projections intersect with primary forest areas could help prioritize areas for conservation under future climatic scenarios.

These opportunities present important directions for refining and expanding the national and regional scale understanding of primary forests in Canada and support more informed, dynamic, and inclusive forest management strategies.

Summary

This project makes progress toward mapping remaining primary forests in Canada, natural forests that have grown without major human impact, such as logging, urban development, or mining. Using national and regional scale datasets, this study identifies forested areas that remain largely ecologically intact. The mapping process involves removing forests that have been disturbed by harvesting, roads, cities, and industrial activities. These primary forests are then grouped by size to show small fragments, larger patches, and vast landscapes. The final maps could help us move further toward an understanding of where Canada's primary forests are likely to still exist and support efforts to protect them for biodiversity, climate stability, and future generations.

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Appendix A

Table: List of available datasets (footnote of Table 1) for primary forest mapping across Canada.

Sl.	Data Category	Data Name	Data Link
1	Forest Cover	Global Forest Change v1.11	https://glad.earthengine.app/view/global-forest-change
2	Forest Cover	Satellite-Based Forest Inventory	https://gee-community-catalog.org/projects/ca_sbfi/
3	Harvesting	Forest disturbances across Canada	https://cdnsiencepub.com/doi/full/10.1139/cjfr-2014-0229#supplementary-materials
4	Harvesting	Boreal Forest Disturbance	https://www.globalforestobservatory.com/canada
5	Harvesting	Canada Landsat Derived Forest harvest disturbance	https://gee-community-catalog.org/projects/ca_forest_harvest/ https://opendata.nfis.org/downloads/forest_change/CA_Forest_Harvest_1985-2020.zip
6	Harvesting	Alberta Vegetation Inventory (AVI) Crown	https://geodiscover.alberta.ca/geoportal/rest/metadata/item/100b275712b442acbda4a0358d8a4951/html https://ouvert.canada.ca/data/dataset/da07e4d0-bf30-45a8-b0d2-a6fcb3939a7a https://open.canada.ca/data/en/dataset/dfb8b498-fa4b-4286-b3ec-58db88aca1cf
7	Harvesting	BC Forest Tenure Harvest (Cutblock) Polygons (FTA 4.0)	https://apps.gov.bc.ca/pub/dwds-ofi/jsp/dwds_pow_current_order.jsp?publicUrl=https%3A%2F%2Fapps.gov.bc.ca%2Fpub%2Fdwds-ofi%2Fpublic%2F&secureUrl=https%3A%2F%2Fapps.gov.bc.ca%2Fpub%2Fdwds-ofi%2Fsecure%2F&customAoiUrl=https%3A%2F%2Faoi.apps.gov.bc.ca&pastOrdersNbr=5&secureSite=false&orderSource=BCDC
8	Harvesting	Harvested Areas of BC (Consolidated Cutblocks)	https://www.arcgis.com/home/item.html?id=2e27a5d899fc4c33a32037d392c00767

Sl.	Data Category	Data Name	Data Link
9	Harvesting	Crown Forest Management Plan Harvest Blocks	https://hub.arcgis.com/datasets/64988a566a11414b8d8684c1c7d66570_0/about
10	Harvesting	Aerial Survey Results	https://hub.arcgis.com/datasets/434a052601a847a2bee16d36be493b6_0/about?locale=en
11	Harvesting	Non-Forest	https://hub.arcgis.com/datasets/a26915d3ff5f41a8a413856308cff57b_0/about?locale=en
12	Harvesting	Stand Improvement	https://hub.arcgis.com/datasets/c4ac6a9e63164d16be29275579591049_0/about?locale=en
13	Harvesting	Vegetation Management	https://hub.arcgis.com/datasets/2d4eb472eeb44753b06a918916717688_0/about?locale=en
14	Harvesting	Harvest-Newfoundland	https://geohub-gnl.hub.arcgis.com/datasets/7d46dd283773447c92b303574009b5b5_1/explore?location=48.585930%2C-54.998988%2C9.93
15	Harvesting	Harvest-Labrador	https://geohub-gnl.hub.arcgis.com/datasets/2a18e3db48634e06896f283bc9478952_1/explore?location=53.669638%2C-59.547300%2C7.62
16	Harvesting	Harvest-Ontario	
17	Harvesting	Bait Harvest Area- Ontario	https://geohub.lio.gov.on.ca/datasets/lio::bait-harvest-area/about
18	Harvesting	QC Harvest	https://diffusion.mffp.gouv.qc.ca/Diffusion/DonneeGratuite/Foret/INTERVENTIONS_FORESTIERES/Recolte_et_reboisement/ https://www.donneesquebec.ca/recherche/fr/dataset/recolte-et-reboisement
19	Harvesting	QC infrastructure clearings	https://pab.donneesquebec.ca/recherche/dataset/infrastuctures-en-milieu-forestier
20	Harvesting	YT Forest Clearings	https://open.yukon.ca/data/datasets/forest-openings
21	Harvesting	NS Crown Land Harvest Plans	https://data.novascotia.ca/Lands-Forests-and-Wildlife/Crown-Land-Harvest-Plans/ag3d-ztdm/about_data

Sl.	Data Category	Data Name	Data Link
22	Harvesting	Canada forest tenures	https://data.globalforestwatch.org/datasets/gfw::canada-forest-tenures/about
23	Human Footprint	Canadian Human Footprint Index	https://borealisdata.ca/dataset.xhtml?persistentId=doi:10.5683/SP2/EVKAVL
24	Human Footprint	Human Access of Canada's Landscapes	https://databasin.org/datasets/0c54d369b225471ea7e9f7999ce94cc0/
25	Waterbody	Hydrology	https://open.canada.ca/data/en/dataset/9d96e8c9-22fe-4ad2-b5e8-94a6991b744b
26	Waterbody	Wetland	https://hub.arcgis.com/datasets/dae233ee7757434cbe7c7b3c0ee336ea_0/about?locale=en
27	Regeneration /plantation	Reforestation	https://hub.arcgis.com/datasets/e7ab6e868f34413a800de7cb06663d17_0/about?locale=en
28	Regeneration /plantation	Regeneration/ plantation	https://gee-community-catalog.org/projects/global_ftype/ https://zenodo.org/records/10701417
29	Fire Disturbance	Canadian National Fire Database	https://cwfis.cfs.nrcan.gc.ca/datamart
30	Fire Disturbance	National Burned Area Composite	https://cwfis.cfs.nrcan.gc.ca/downloads/nbac/
31	Fire Disturbance	CA Forest Fires	https://opendata.nfis.org/mapserver/nfis-change_eng.html
32	Fire Disturbance	CA Wildfire dNBR	https://opendata.nfis.org/mapserver/nfis-change_eng.html
33	Fire Disturbance	Large forest fires in Canada	https://doi.org/10.1029/2001JD000484
34	Fire Disturbance	Fire	https://mli.gov.mb.ca/forestry/index.html
35	Fire Disturbance	Annual Forest Fire	https://data.princeedwardisland.ca/datasets/72ada61c9337405b9abe3e3591e1acfe_0/explore
36	Fire Disturbance	Canadian Fire Spread Dataset	https://osf.io/f48ry/files/osfstorage

Sl.	Data Category	Data Name	Data Link
37	Fire Disturbance	Active Wildfires in Canada	https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/activefires
38	Fire Disturbance	National Fire Situation Report	https://ciffc.net/situation/2025-05-24
39	Fire Disturbance	Ontario-Forest Fire Info Map	https://www.lioapplications.lrc.gov.on.ca/ForestFireInformationMap/index.html?viewer=FFIM.FFIM
40	Insect	Hemlock Looper	https://hub.arcgis.com/datasets/94f56206b6e7472582820a78bf58a246_0/about?locale=en
41	Insect	Spruce Budworm	https://hub.arcgis.com/datasets/94f56206b6e7472582820a78bf58a246_1/about?locale=en
42	Insect	Spruce Budworm L2 Mapping	https://hub.arcgis.com/datasets/9a96d45906f74b578294d5c82eac995d_0/about?locale=en
43	Insect	Digitized Pest Management Records	https://hub.arcgis.com/datasets/6369648ad18e42ec80464f1fecff5ae0_0/about?locale=en
44	Insect	Forest insect damage event	https://geohub.lio.gov.on.ca/documents/lio::forest-insect-damage-event/about
45	Other disturbances	Roads	https://conbio.onlinelibrary.wiley.com/doi/10.1111/csp2.12656 https://osf.io/28ua4/
46	Other disturbances	Pipelines (NB)	https://open.canada.ca/data/en/dataset/4188dacc-07c5-f72c-cfb1-cd505fcd4eb4
47	Other disturbances	Dams	https://open.canada.ca/data/en/dataset/fd4369a4-21fe-4070-914a-067474da0fd6
48	Other disturbances	Roads and other data	https://open.canada.ca/data/en/dataset/2dac78ba-8543-48a6-8f07-faeef56f9895
49	Rail	Rail	https://natural-resources.canada.ca/science-data/science-research/geomatics/download-directory-documentation
50	Rail	North American Atlas-Railroads (FTP)	https://natural-resources.canada.ca/science-data/science-research/geomatics/download-directory-documentation

Sl.	Data Category	Data Name	Data Link
51	Road	Ferry Route	https://natural-resources.canada.ca/science-data/science-research/geomatics/download-directory-documentation
52	Road	Road	https://natural-resources.canada.ca/science-data/science-research/geomatics/download-directory-documentation
53	Road	North American Atlas - Railroads (FTP)	https://natural-resources.canada.ca/science-data/science-research/geomatics/download-directory-documentation
54	Mining Disturbance	Canada petroleum and natural gas	https://data.globalforestwatch.org/datasets/gfw::canada-petroleum-and-natural-gas/about
55	Mining Disturbance	Canada mining permits	https://data.globalforestwatch.org/datasets/gfw::canada-mining-permits/about
56	Other disturbances	Mines	https://open.canada.ca/data/en/dataset/000183ed-8864-42f0-ae43-c4313a860720
57	Other disturbances	Mines	https://open.canada.ca/data/en/dataset/92dbea79-f644-4a62-b25e-8eb993ca0264
58	Other disturbances	Towns and urban zones	https://open.canada.ca/data/en/dataset/306e5004-534b-4110-9feb-58e3a5c3fd97
59	Other disturbances	Major infrastructure	https://open.canada.ca/data/en/dataset/fd4369a4-21fe-4070-914a-067474da0fd6
60	Road	Forestry Roads	https://hub.arcgis.com/datasets/5fc5e3ce50b24148bea6ee415de2d8e8_0/about?locale=en