FINAL REPORT

REVIEW OF THE CURRENT STATE OF KNOWLEDGE FOR DEFINING, IDENTIFYING AND CLASSIFYING PRIMARY FOREST IN CANADA

2024

habitat

LA NATURE À L'ŒUVRE

Habitat is an environmental solutions company founded in 2017 (first known as Eco2urb) and based in Montreal. It offers nature-based solutions to fuel and propel its customers' ecological transition, particularly in a context of green recovery.

Habitat was born out of a pooling of the expertise of three leading laboratories in the human and natural sciences. The company is headed by Professors Dupras, Gonzalez and Messier, all internationally renowned in their fields.

In recent years, Habitat has catalyzed the ecological transition of a diverse clientele. The team collaborates with numerous universities, research centers and non-governmental organizations to facilitate the implementation of scientific work related to ecology, forestry and land use planning. We propose innovative approaches and state-of-the-art environmental strategies.

Habitat's team of scientists will guide you in the sustainable management of ecosystems, the conservation of biodiversity and the consideration of the services rendered by your natural infrastructures, by applying the best available science.

Our mission is to accelerate your ecological transition with solutions rooted in nature and science.

Project Team

Report writing and analysis

Geneviève Fortin-Blanchard, M.Sc. Project Manager

Médéric Durand, M.Sc. Analyst

Eva Delmas, Ph.D., Analyst

Project Coordination

Vincent Lemire, M.Sc., Project Manager

Scientific Direction

Sylvia Wood, Ph.D., Director of Science and Research

Suggested Citation:

Habitat. 2024. Review of the current state of knowledge for defining, identifying and classifying primary forest in Canada. For World Wildlife Fund for Nature. 50p.

TABLE OF CONTENTS

LISTE DES FIGURES

1. INTRODUCTION

Climate change represents one of the most pressing global challenges of our time, with its impacts permeating nearly every aspect of the natural world and human society. Central to the discourse on climate change is the role of forests, particularly primary forests, which are integral in mitigating environmental change. Primary forests—those that have remained largely undisturbed by human activity—are crucial in the fight against climate change due to their unparalleled capacity to sequester carbon dioxide (CO2). These forests act as significant carbon sinks, helping to regulate atmospheric CO2 levels and thereby stabilizing global temperatures (Pan et al., 2011). The preservation of these forests is not only vital for climate stability but also for maintaining biodiversity, as they provide habitat for a vast array of species that might be lost in more disturbed environments (Barlow et al., 2016).

Forest degradation, however, poses a severe threat to these critical ecosystems. Degradation refers to the decline in the quality of forest ecosystems due to activities such as logging, mining, and agricultural expansion, which compromise their ecological integrity (Murray et al., 2011). Unlike deforestation, which results in the complete loss of forest cover, degradation involves the partial loss of ecological functions and services. This process not only diminishes the carbon storage capacity of forests but also affects their ability to support wildlife and regulate local and global climates (Houghton, 2003). Consequently, accurately defining and identifying primary forests is essential for effective conservation strategies and policymaking.

Establishing clear definitions of primary forests is crucial for developing targeted conservation policies and managing forest resources sustainably. A precise definition allows for better monitoring and protection measures, ensuring that the remaining primary forests are preserved against encroaching threats (Larsen et al., 2017). Policymakers must integrate scientific knowledge on forest ecosystems with practical conservation measures to address both the direct and indirect effects of forest degradation. This approach includes promoting sustainable land-use practices, enforcing regulations to prevent illegal logging, and supporting reforestation and afforestation efforts (FAO, 2020). By defining and protecting primary forests, policymakers can enhance their efforts to combat climate change and preserve biodiversity, ultimately contributing to a more resilient and sustainable future for both people and the planet.

There is little consensus amongst researchers regarding the ‘naturalness’ and ‘intactness’ concepts often brought up while defining primary forests. How long after a major human disturbance can an ecosystem be considered ‘natural’ (and thus primary) again? How is a reference state chosen? This is especially difficult to determine for forested ecosystems that undergo a short stand-replacing disturbance return cycle and are thus in constant modification. Higgs et al. (2014) suggest moving away from this ‘ecosystem as an artifact’ view and towards using historical conditions more as a guide than a template or benchmark.

In this context, WWF mandated Habitat to do a literature review of primary forest. The mandate which was to define, identify, and map primary forests in Canada is crucial for advancing forest conservation and management strategies. Primary forests, often referred to as old-growth forests, are ecosystems that have developed naturally over long periods without significant human intervention. Their preservation is vital not only for maintaining biodiversity but also for sustaining ecological processes that regulate climate and support wildlife. The primary objectives of this mandate are to frame a comprehensive definition of primary forests, assess existing definitions, review recent research, and develop actionable recommendations for recognition and mapping.

The initial objective involves evaluating the consistency and gaps within current definitions of primary forests in Canada. This assessment will be followed by a review of recent research and mapping efforts, focusing on the methodologies, data, and approaches employed. This includes comparing these approaches with the Convention on Biological Diversity's definition to identify potential shortcomings. The final goals are to provide specific recommendations for the recognition and mapping of primary forests and to develop supporting materials for engaging with Indigenous communities and other key stakeholders.

To achieve these objectives, the work plan will include several key steps. First, we will review recent scientific articles and grey literature to identify current methodologies and their limitations regarding primary forests. This review will help in understanding established standards for recognizing primary forests, including tree species, age structure, climate hazards, and disturbance patterns.

A critical aspect of this process is incorporating Indigenous perspectives. Indigenous communities have deep cultural and spiritual connections to forests, and their knowledge offers valuable insights into the historical and ecological significance of these areas. Therefore, our approach will prioritize Indigenous perspectives, integrating their understanding of the forest into the definition and mapping methodology.

We will propose an operational definition of primary forests that encompasses physical characteristics, Indigenous knowledge, and the official definition set by the Food and Agriculture Organization (FAO). This will be complemented by recommendations on the methodology for mapping primary forests, utilizing tools such as online research platforms, keywords targeting relevant literature, and geospatial data.

The methodology will involve:

1. Reviewing global and national mapping techniques for primary forests.
2. Identifying relevant public datasets and evaluating their data types, resolution, and temporal coverage.
3. Considering the limitations and potential pitfalls of mapping efforts, including which criteria might be challenging to map and exploring potential data sources to address these gaps.
4. Integrating Indigenous knowledge into the mapping process to ensure that the perspectives of Indigenous communities are reflected in the final outputs.

Incorporating Indigenous perspectives in forestry and conservation is essential for several reasons. Indigenous communities have stewarded their lands for millennia, developing a profound understanding of forest ecosystems that extends beyond scientific knowledge. Their insights into traditional practices, ecological relationships, and cultural values provide a more holistic view of forest health and management. Recognizing Indigenous knowledge and practices in defining and mapping primary forests not only respects their rights and contributions but also enhances the effectiveness of conservation efforts by integrating diverse ways of understanding and managing natural resources.

2. OVERVIEW OF CANADA'S FORESTS

2.1 CANADA'S TWELVE FORESTED ECOZONES

As of the latest National Forest Inventory survey (Wulder et al., 2024), forests cover an estimated area of 361 million hectares. Of this vast extent, approximately 90.4% of Canada's forest is publicly owned – this includes protected areas, Crown Land as well as land-leases and "cut blocks" managed by the timber

industry. The forestry industry manages 45% of these public forests, while approximately 2.1% of Canada's forested area is under the ownership of its Indigenous Peoples through various treaties and concessions (*e.g.* the Indian Act or the Framework Agreement on First Nation Land Management Act).

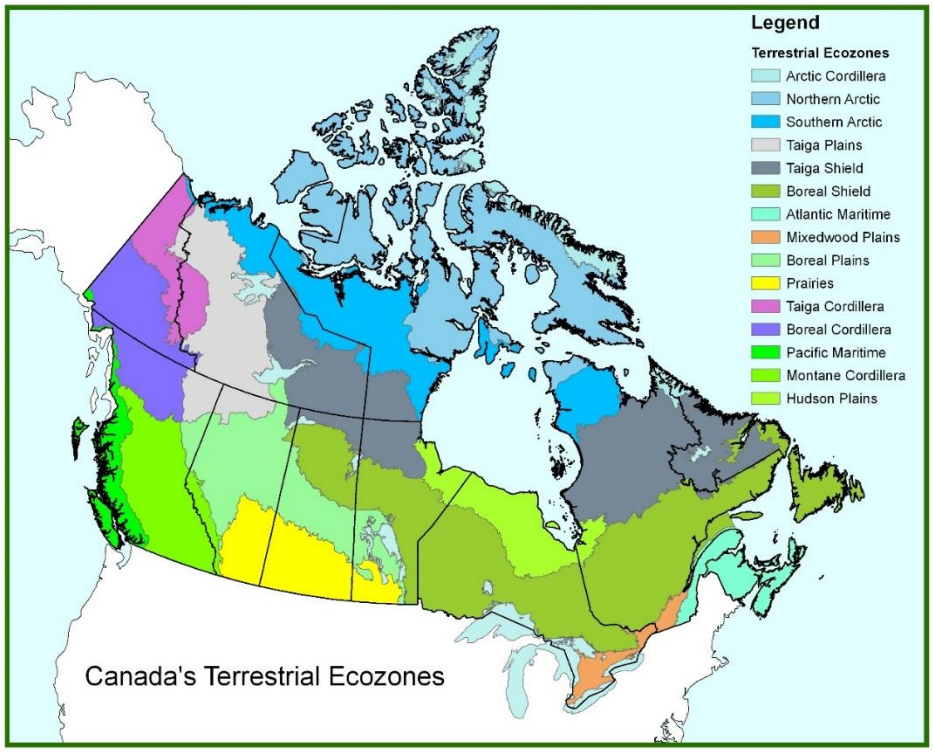

Figure 1. Canada's fifteen terrestrial ecozones (Government of Canada, n.d.; Wiken et al., 1996)

At the federal level, Canada's terrestrial lands can be divided into fifteen ecozones, with twelve of them being predominantly forested (Wiken et al., 1996). These forested ecozones highlight at the scale of Canada the dominant forest species, disturbance dynamics, as well as commonality in soil properties and climate between each ecozones. Canadian forests can be described following a South to North gradient, wherein the deciduous tree species of the temperate ecozones are dominant in southern regions, particularly of southern Ontario and Québec, but rapidly make room for evergreen, cold-adapted coniferous species typical of boreal tree species thus forming a heterogeneous, mixed forest matrix.

2.1.1 Forest disturbances and their effect on structure

Historically, forest fires and pest outbreaks are the main sources of natural disturbance in temperate and boreal forests (including taiga ecozones). More than twenty years ago, wildfires were shown to burn an average of 2 million hectares Canada-wide. The yearly area burned widely varies from year to year, with the 2021 fire season burning an estimated 4.3 million hectares across Canada (Natural Resources Canada, 2022). As the fire season lengthens, this average area burned is thought to be significantly increasing (Hanes et al., 2019). The lengthening of the fire season is a result of a process known as climate forcing, itself a product of global change/global warming. Thus, there is an increasing interest amongst researchers towards distinguishing wildfires happening under normal, baseline climatic conditions from those originating from human-lead climate change (eg. Grondin et al., 2018; Hennebelle et al., 2018).

Wildfires naturally vary in severity – from small surface fires that only burn the lower vegetation strata, up to the extent of being a stand replacing disturbance. On the other hand, pest outbreaks (e.g. Spruce budworm, Pine beetle, Forest tent caterpillar) are selective disturbances, often targeting a particular tree species within a stand, and often lead to large-scale defoliation events which can in turn lead to heightened wildfire risks.

Recent studies focused on natural disturbances in unmanaged temperate and boreal forests have shown high within-biome variability, in terms of the number and size of disturbances in the recent past (2001-2014). However, there is little overall difference between biomes in terms of frequency or extent of disturbance, nor a strong latitudinal gradient (Seidl et al., 2020). Areas of low disturbance activity were characterized by wind and pest outbreaks, while areas with high disturbance activity were primarily affected by fires. In these unmanaged forests, boreal forests experienced predominantly high disturbance activity linked with wildfires, while temperate forests mostly experienced low and moderate disturbance activity, more typical of wind and pest outbreaks (Runkle, 1985; Wiken et al., 1996).

These trends are supported by previous research which suggest that wildfires are not the main disturbance dynamics affecting the structure and composition of the temperate forest ecozones covering southern Québec, Ontario nor the maritime provinces – however, they are known to occur in the drier mixed coniferous stands that can also be found within these forest types (Fischer et al., 2013). Across Canada's Boreal ecozones, wildfires are shown to become the main source of disturbance shaping the forest landscape dynamics (Coogan et al., 2021; Jiang et al., 2009), with shorter fire-return intervals favoring short-lived poplar (*Populus*) and birch (*Betula*) stands, as well as the fire-adapted, coniferous spruce (*Picea*) and jack pine (*Pinus banksiana*) stands (Figure 2).

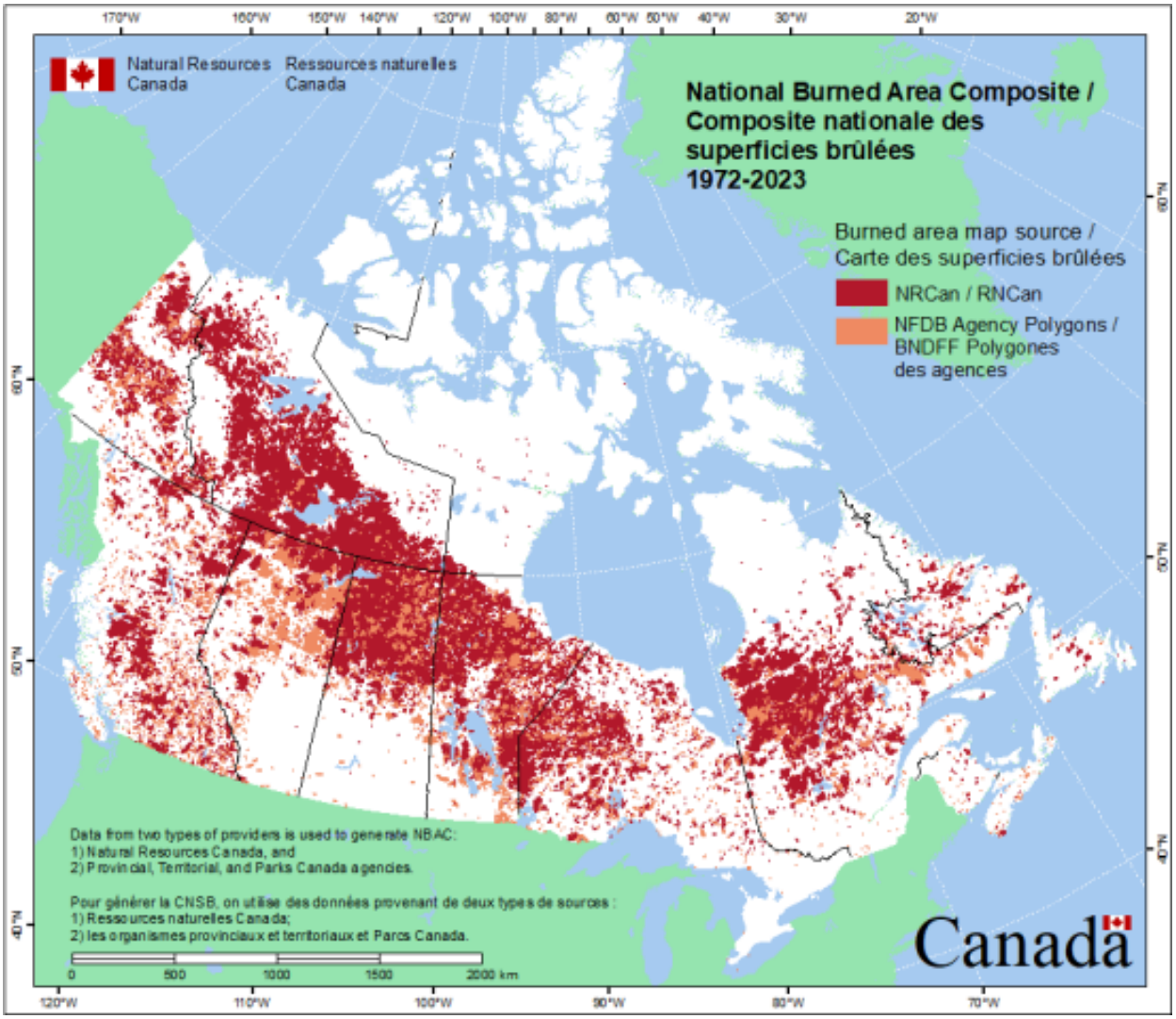

Figure 2. Burned area across Canada, 1972-2023. See Boulanger et al (2014) for an in-depth review of the distribution of total burned area across Canada.

The dominance of wildfire and pests as the main stand-replacing disturbance dynamics results in a higher proportion of younger forest stands than in the Southern mixed and temperate forests. North of the boreal forest ecozones, as the growing season shortens, the closed-canopy boreal stands start transitioning towards the semi-open, fire prone taiga landscape. Canada's oldest forests are located in British Columbia, west of the Rockies, where a wet and comparatively cooler climate favor hundred to millennia-long fire cycles and the presence of temperate rainforests (Coogan et al., 2021; Sanborn et al., 2006). In the montane cordillera ecozone of central British Columbia and western Alberta, forest fires are known to be a somewhat important disturbance dynamics, along with avalanches and windthrows (Fischer et al., 2013; Wiken et al., 1996). Years of fire suppression politics have led to increasingly large wildfires, both natural and anthropogenic, with mean fire return intervals averaging 150 years (Jiang et al., 2009; Rogeau et al., 2016).

Finally, forests are mainly absent from the Canadian prairies, where human fire suppression and large-scale agricultural practices maintain tall-grass ecosystems (Wiken et al., 1996). In Québec's lower Saint-Lawrence region and southern Ontario – where 90% of Ontario's population lives – the landscape has been heavily modified over the course of hundreds of years of urban sprawl and agriculture: Less than 15% of southern Ontario's land cover is forested, with much of these forests having been harvested at some point.

Land-use changes due to agriculture and urban sprawl only represent a fraction of anthropogenic disturbances affecting Canadian forests, which include deforestation for mining, oil and gas, and hydroelectricity. Timber harvest is the biggest driver of anthropogenic disturbance, with 710,333 hectares harvested in 2020 (Natural Resources Canada, 2022). Most of the industrial large-scale harvesting occurs in the taiga and northern boreal ecozones (Gauthier et al., 2015), which also tend to be prone to wildfires (Boulanger et al., 2014). Similarly to pest outbreaks, timber harvest increases the risk of wildfires. Consequently, around 10% of fires were directly initiated by human activity (Hanes et al., 2019). As will be discussed in latter sections of this review of the literature, forests grown after timber harvest, whether planted or not, are generally considered non-primary.

2.1.2 Land-use history and legacy impacts on forests

Historical land-use changes may affect the structure and/or integrity of forests – a concept that is closely associated with the term the concept of primary forests – both through long lived legacy effects, and indirectly by affecting landscape-level ecological processes such as wildfire patterns. While disturbance and forest loss are key elements of forest dynamics across Canada, the type of disturbance can have a strong influence on the structure and composition of the forest that returns. Between 2000 and 2013, Canada lost more than 14 million hectares of its intact forest landscapes area, defined as a large, seamless mosaic of primary and non-primary forests (Potapov et al., 2017) through both natural and anthropogenic disturbance and logging. This loss alone in Canada accounts for 15% of the global intact forest landscape area loss. Depending on the source and intensity of the disturbance, there can be important lasting legacies of anthropogenic impact on forests that affect their structure and function, and on adjacent forests as well.

At the stand level, numerous studies have documented the impacts of different land use histories on successional trajectories post-disturbance. Sass et al. (2018) compared successional patterns in old-growth hemlock (*Tsuga canadensis*) and white pine (*Pinus strobus*) stands in New Hampshire that were first logged in 1930 and then underwent a stand-replacing disturbance (Hurricane) shortly after. Compared to neighboring old-growth stands that were not logged, the stands that were historically harvested showed a similar species composition, yet the tree and microtopography density and dead wood biomass were significantly lower. This echoes the importance of the structural criteria often found in the literature regarding old-growth forests ("presence of dead wood", "microtopography", see Issekutz [2020] and Mosseler et al. [2003]) and highlights the lasting legacies of human impact. Similarly, a study focusing on the deforestation and agricultural slash fire practices in Wisconsin (Rhemtulla et al., 2009) shows that despite ~80 years of afforestation in many parts of the state, the total canopy cover of certain late successional species (*T. canadensis, P. strobus*) has significantly decreased in favor of early successional species. In the naturally fire-regulated south-Wisconsin savannas, historical fire-suppression

practices have led to a landscape-wide shift towards shade tolerant species such as maple (*Acer spp.*) and ash (*Fraxinus spp.*).

At regional scales, studies have shown that large-scale harvesting has the potential to shift regional bioclimatic domains across landscapes, suggesting that the impacts of harvesting can extend beyond the actual cutblock sites. Within the Boreal shield, Grondin et al. (2018) show that harvesting practices have the capacity to change the bioclimatic domain on a landscape level *i.e.* the climax vegetation type and the successional pathways leading up to it (Bergeron & Fenton, 2012). This process happens when sustained intensive logging and deforesting practices push forests composition and age structure outside of their normal range of variability (Grondin et al., 2018; Hennebelle et al., 2018).

This highlights the potential large-scale, regional impact of harvesting practices: while a given forest ecosystem might be historically untouched by logging practices, extra-local and regional harvests may have the capacity to significantly impact its ecology. Through secondary impacts such as changes in the fire regime or landscape level losses of certain high-value species favored by the logging industry, stand-level resilience may decrease and influence succession pathways (Grondin et al., 2018). At regional scales, studies have shown that large-scale harvesting has the potential to shift regional bioclimatic domains across landscapes, suggesting that the impacts of harvesting can extend beyond the actual cutblock sites. Along with the boreal shield, Grondin et al. (2018) show that harvesting practices have the capacity to change the bioclimatic domain on a landscape level *i.e.* the climax vegetation type and the successional pathways leading up to it (Bergeron & Fenton, 2012).

This process happens when sustained intensive logging and deforesting practices push forests composition and age structure outside of their normal range of variability (Grondin et al., 2018; Hennebelle et al., 2018). This highlights the potential large-scale, regional impact of harvesting practices: while a given forest ecosystem might be historically untouched by logging practices, extra-local and regional harvests may have the capacity to significantly impact its ecology. Through secondary impacts such as changes in the fire regime or landscape level losses of certain high-value species favored by the logging industry, stand-level resilience may decrease and influence succession pathways (Grondin et al., 2018).

Road building, stream draining, and canopy loss all affect landscape connectivity. The impact of such disturbances may appear localized at first, but by fragmenting the landscape, it has been shown to alter the temperature and humidity in edge areas, leading to shifts in species composition and a number of ecological functions (e.g. decomposition rates) (Burton, 2002; Harper et al., 2015). Moreso, the impact of connectivity loss and fragmentation diffuses throughout neighboring ecosystems by impeding certain species' dispersal capabilities. This affects ecosystemic resilience on a landscape level and modifies certain woodland species' natural (i.e. pre-anthropic) ecological patterns (Baguette et al., 2013; Liu et al., 2014). Road building, stream draining, and canopy loss all affect landscape connectivity.

There is a gap in the literature regarding human-induced shifts in canopy cover at the prairie-forest ecotone in Canada's prairies, although this subject has been covered at large in the American prairies (DeSantis et al., 2011; Morgan et al., 2020). A recurring conclusion is that anthropogenic land use change and fire suppression practices have modified wildfire patterns, indirectly impacting stable regional ecosystem states. Consequently, shifts from prairie to forest along the ecotone modify forest age and their overall 'naturalness'.

Grondin et al. (2018), Rhemtulla et al. (2009) and Sass et al. (2018) all underline the problems and possible pitfalls often encountered while trying to define the naturalness and intactness of an ecosystem.

2.1.3 Traditional landscape legacies

Beyond modern-day land-use change and forestry practices, we know that Indigenous communities have inhabited forest landscape across Canada for millennia and have long relied on forests as integral components of their culture and identity. One striking example is the utilization of cedar trees, which can live for over a millennium, providing tangible evidence of First Nations' use and management of forest resources. Cedars were prized for their versatile bark, collected in various forms such as long strips or large sheets. This bark served multiple purposes including basketry, clothing, mats, cordage, roofing, and shelter construction, among others (Turner, 2020).

Ethnographic data, coupled with dendrochronology, the dating of tree rings, suggests that the presence of multiple scars on a single cedar tree signifies not only long-term management practices but also a profound connection to specific trees and harvesting sites (Turner et al., 2013). This illustrates the deep cultural significance and sustainable management practices of Indigenous communities in Canada.

Furthermore, forests have been intertwined with burial practices among First Nations, evidenced by changes in vegetation near burial sites. Indigenous communities would cultivate and plant specific types of vegetation as part of funeral rituals, demonstrating a spiritual and ceremonial connection to the land (Turner et al., 2013).

Moreover, economically, forests provide critical resources for subsistence living, such as food, medicine, and materials for shelter and tools. Traditional practices like hunting, fishing, and gathering are vital for the livelihoods of Indigenous peoples. Additionally, Indigenous communities often engage in sustainable forest management practices, such as controlled harvesting and fire management, which are crucial for their local economies.

On a second hand, environmentally, Indigenous communities play a key role in biodiversity conservation through their deep understanding of local ecosystems and sustainable practices. Their stewardship helps maintain healthy forest ecosystems, contributing to carbon sequestration and climate regulation, which are essential in mitigating climate change. (Van Bavel et al., 2022)

In addition, legally and politically, forests are often located on traditional Indigenous territories, making the recognition and respect of Indigenous land rights and sovereignty critical. Efforts to involve Indigenous communities in forest management decision-making processes are increasing, highlighting the importance of collaborative management frameworks. These frameworks enhance the protection and sustainable use of forests while respecting Indigenous rights and knowledge.

Overall, forests have played a crucial role in the development and preservation of Indigenous culture and identity in Canada. They serve as more than mere resources; they are living entities deeply intertwined with the spiritual, cultural, and practical aspects of Indigenous life. These realities helped us determine the scope of what is achievable while creating a definition of primary forests suited for Canada and to identify its gaps. It also allowed us to further steer this review of the literature towards an outcome that is representative of Canada’s history and geography.

2.2 KEY DEFINITIONS

2.2.1 Primary forest definitions in the scientific literature

Primary forests, often referred to as “intact” or “virgin forests”, generally refer to pristine ecosystems largely unaffected by human interference. In addition to being culturally significant, these forests hold immense ecological value and are defined by several key structural, functional and historical disturbance characteristics. Importantly, primary forests are also recognized for their crucial role in supporting biodiversity and ecological processes. These forests serve as important habitats for numerous plant and animal species, many of which may be rare or endangered. Additionally, primary forests play a significant role in regulating local and global climate patterns through carbon sequestration and storage. Their intact nature allows for the maintenance of healthy soil, water, and nutrient cycling processes, contributing to the overall stability of ecosystems. As such, primary forests are invaluable ecosystems that have remained largely untouched by human activity, maintaining their natural integrity and ecological processes. Their identification on the landscape and preservation is crucial for biodiversity conservation and the maintenance of ecosystem services

In 2001, the Secretariat for the Convention on Biodiversity Diversity defined primary forests as:

> “*A primary forest is a forest that has never been logged and has developed following natural disturbances and under natural processes, regardless of its age. It is referred to "direct human disturbance" as the intentional clearing of forest by any means (including fire) to manage or alter them for human use. Also included as primary, are forests that are used inconsequentially by indigenous and local communities living traditional lifestyles relevant for the conservation and sustainable use of biological diversity*.”

More recently, the definition has been updated by the Food and Agriculture Organization (FAO, 2018) which describes primary forests as being:

> ‘‘*Naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities, and the ecological processes are not significantly disturbed. Some key characteristics of primary forests are 1) They show natural forest dynamics, such as natural tree species composition, occurrence of dead wood, natural age structure and natural regeneration processes; 2) The area is large enough to maintain its natural ecological processes; and 3) There has been no known significant human intervention or the last significant human intervention was long enough ago to have allowed the natural species composition and processes to have become re-established.* ’’

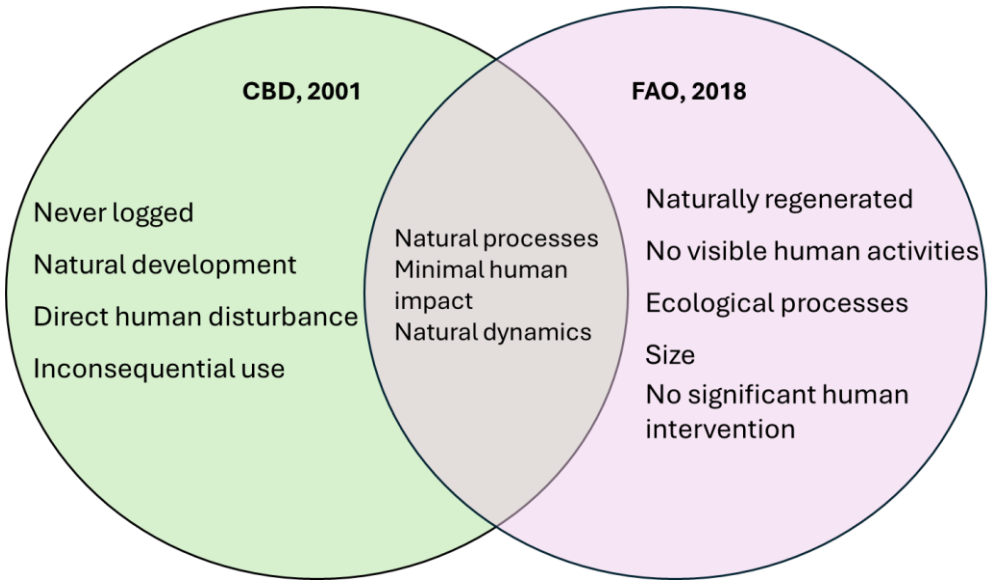

Figure 3. Venn diagram showing the overlap between the criteria used in the CBD (2001) and FAO (2018) definitions of primary forests

While most organizations and countries adopt one of these two definitions, several key studies have sought to refine the criteria that can be used to define and identify primary forests from other potential forest types (see next section for other terminologies). For example, Dubois (2005) simply defines primary forests as forests that originally covered a region before human-induced environmental changes. Buchwald (2005) expands on this definition, describing primary forests as relatively intact forests essentially unmodified by human activity for at least sixty to eighty years. While some low-level human activities may have occurred, such as hunting, fishing, or harvesting forest products, significant interventions like logging or agriculture are absent.

In their definition of primary forest, Mackey (2015) and Turubanova et al. (2018) both emphasize the absence of visible human activities and disruptions to ecological processes. Turubanova et al. (2018) offer an operationalizable definition focused on anthropogenic disturbance across large swaths of tropical forests. They specify that primary forests include those affected by selective logging or other disturbances that have not completely altered forest composition and structure.

Kormos et al. (2018) seek to provide a comprehensive definition, highlighting that primary forests are largely undisturbed by industrial-scale activities, possess a full range of successional stages, have a continuous tree canopy cover, and exhibit unpolluted soil and water. These forests are more likely to retain their native plant and animal species with minimal introduction of exotic species.

Finally, Peterlssekutz (2020) and Barredo (2021) both stress that primary forests are characterized by their relatively intact nature, following natural dynamics, composed of native species, and showing no indications of human activities.

Together, these studies suggest that there are several common qualities that can be used to identify and distinguish primary forests across different landscapes. In the following subsections, we will define the terms old-growth forest, virgin forest, and secondary forest. It is important to define these terms because they are widely used across the literature, often interchangeably, leading to poor coherence (Wirth et al.,

2009). Furthermore, most of these terms are used (interchangeably) in official works across multiple Canadian provincial and territorial governmental instances. Therefore, to fully understand the differences between primary forests and these different terms, we choose to highlight the subtleties that exist between them. We believe the concept of primary forest can serve as an umbrella to the terms described below.

2.2.2 Old-growth

Old-growth forests are hailed as bastions of ecological richness and biodiversity, representing the result of centuries of natural forest growth. These forests, characterized by their age, structure, and unique ecological attributes, play a vital role in maintaining the health of ecosystems worldwide.

According to the Secretariat of the Convention on Biological Diversity, old-growth forests can be categorized into primary or secondary forests. What distinguishes them is their age and the accumulation of structures and species characteristic of mature ecosystems. These forests have matured to a point where they exhibit distinct features not found in younger forests of the same type.

Identifying old-growth forests involves considering specific criteria. As outlined by Issekutz (2020), these criteria include:

1. Presence of Key Old-Growth Tree Species: Old-growth forests are often characterized by the presence of certain tree species that have reached maturity. These trees typically exhibit crown closure of 30% or more, indicating a mature canopy structure.

2. Presence of Indicator Lichens: Lichens serve as important indicators of environmental quality and forest health. The presence of specific lichen species, identified through established identification charts or studies, can indicate the maturity and ecological significance of a forest.

3. Abundance of Dead Wood: Old-growth forests are known for their accumulation of dead wood, which plays a crucial role in nutrient cycling, habitat provision, and ecosystem resilience. Assessing the amount of dead wood, using methods such as observing mound topography on the forest floor and soil sampling, provides insights into the ecosystem processes at play

Combining these criteria allows for a comprehensive assessment of old-growth forest ecosystems can be achieved, aiding in their conservation and management. Protecting these forests is crucial not only for preserving biodiversity but also for mitigating climate change, as these forests store significant amounts of carbon and contribute to global carbon sequestration efforts.

The European Environment Agency also describes an old-growth forest as a primeval, ancient wilderness that is in a pristine condition. It can also be defined as a forest that has not been disturbed by an anthropogenic presence. They also believe that an old-growth forest can be classified by the age of the trees.

Using the above definition, we can therefore conceptualize old-growth forests as representing the peak – or climax – of natural forest development, characterized by their age, structure, and ecological complexity. By employing specific criteria for identification and conservation, we can ensure the preservation of these invaluable ecosystems for future generations.

2.2.3 Virgin forests

Virgin forests represent the epitome of untouched nature, where human interference has been minimal or non-existent. The concept of virgin forests, also known as primeval, or pristine forests, denotes environments that have developed naturally, free from human influence, under the forces of natural ecological processes. In contrast, the term "natural forests" encompasses areas that have experienced some degree of human impact but still exhibit characteristics of natural ecosystems.

Austria played a pioneering role in evaluating the naturalness of its forests in the early 1990s, leading to a broader understanding of forest ecosystems across Europe. The distinction between virgin and natural forests lies in the extent of human intervention. Virgin forests remain largely untouched by human hands, preserving their original structure and composition. While most virgin forests are considered old-growth, the term is not limited to climax stages of forest development (Barredo et al., 2021).

In contrast, natural forests have experienced some level of human influence, albeit to a lesser extent than managed or planted forests. Despite this influence, natural forests maintain characteristics of original forest cover and undergo regeneration through natural succession processes. However, anthropogenic traces from past activities may still be evident.

The terminology surrounding forest classification has been subject to debate and standardization efforts by organizations like the Food and Agriculture Organization of the United Nations (FAO) and the Ministerial Conference on the Protection of Forests in Europe (MCPFE). While "virgin forest" and "forest undisturbed by man" are often used interchangeably, the latter term encompasses a broader spectrum of naturalness, allowing for some degree of past human influence (Forest Europe, 2020).

The distinction between virgin and natural forests hinges on the level of human interference throughout their development. Virgin forests represent pristine ecosystems untouched by human hands, while natural forests exhibit some degree of anthropogenic influence but maintain characteristics of original forest cover and natural succession processes. Understanding and preserving these forests are crucial for conserving biodiversity and maintaining ecological balance in forest ecosystems.

2.2.4 Secondary forests

Secondary forests, as described by Chokkalingam and De Jong (2001), represent dynamic ecosystems that emerge following significant disturbance to the original forest vegetation. These forests undergo a process of secondary succession, ultimately developing into climax communities or primary forests over time.

Key characteristics of secondary forests include:

1. Significant Disturbance: Secondary forests arise following substantial disruption to the original forest vegetation. This disturbance can result from natural events such as fires, storms, or human activities like logging or land clearing.

2. Natural and/or Human-Initiated Disturbance: The disruption to the original forest vegetation may stem from natural occurrences or human intervention. Whether caused by forest fires, agricultural expansion, or other human activities, the disturbance sets the stage for secondary forest regeneration.

3. Progressive or Single-Point Disturbance: The disturbance to the original forest vegetation can occur gradually over an extended period or abruptly at a single point in time. Regardless of the timing, the outcome is the regeneration of a new forest ecosystem.

4. Regeneration and Redevelopment: Secondary forests are characterized by ongoing regeneration and redevelopment processes. Most of the regeneration occurs spontaneously, driven by natural processes such as seed dispersal and germination.

5. Distinct Forest Structure and Species Composition: A defining feature of secondary forests is their divergence in forest structure or canopy species composition compared to nearby primary forests on similar sites. This difference reflects the impact of the initial disturbance and subsequent regeneration dynamics.

Secondary forests play vital roles in ecosystem recovery, biodiversity conservation, and carbon sequestration. While they may initially exhibit distinct characteristics from primary forests, they contribute to landscape heterogeneity and provide essential habitats for a variety of plant and animal species.

Understanding the dynamics of secondary forests is crucial for effective forest management and conservation strategies. By recognizing their importance in the context of landscape ecology and ecosystem resilience, we can ensure the sustainable management and restoration of these valuable forest ecosystems for future generations.

2.2.5 Federal, provincial and territorial definitions

Each province and territory in Canada have their own understanding of primary forests, although the government of Canada has adopted the definition outlined by the Food and Agriculture Organization (FAO) in 2018 (see above). This definition describes primary forests as naturally regenerated forests of native tree species, where human activities are not visibly present, and ecological processes remain undisturbed. Despite the official adoption of the FAO definition federally, most provinces do not use the term “primary forest” in the policies they have developed to date, but instead focus on the identification, protection and management of “old growth” forests. In Quebec, similar policies have instead referred to “virgin forests”, defined as forests untouched by human activity, or primitive forests, which lack anthropic influence.

It's also important to note that not all provinces and territories use these terms for conservation purposes; many provinces use several different words for specific contexts. For example, British Columbia uses the word old-growth for the type of forest in its territory, while others choose to define the term that will best fit in a land use context. When they do use the term primary forest, they do not necessarily use the FAO term. In fact, each province acts independently of the decisions of the federal government when it comes to defining certain terms for activities that take place on its own territory.

In addition to the last point, in British Columbia, due to the unique nature of its forests, the concept of old-growth is predominantly used for the purpose of conservation. The government defines old-growth forests based on age (140 to 250 years), characteristics such as standing dead trees and layered canopy, and their role in biodiversity and carbon storage. Conservation efforts in British Columbia are directed towards these old-growth forests (British Colombia Government, n.d.).

Alberta's forests differ from those in coastal British Columbia, with shorter lifespans due to natural disturbances. Their definition of undisturbed forest is not specific but is similar to the definition used to explain what virgin forests, primary or secondary forests are – that is, depending on the level of anthropic disturbance and the origin of the documents (Ex. Ministry of forestry and Parks vs Ministry of Agriculture and Irrigation).

In New Brunswick, the term old-growth forests and virgin forests are interchangeable. According to the province, those type of forests provides essential habitats for diverse wildlife, while also acting as significant carbon sinks. However, these forests are now often located in parks or areas inaccessible to forestry companies. (New Brunswick, n.d.)

In Nova Scotia, once abundant with old-growth forests, conservation efforts under the Old-growth Forest Policy aim to protect remaining areas and restore ecosystems. These forests are viewed as late-successional ecosystems shaped by prolonged development and disturbances (Nova Scotia Government, 2021).

Similarly, in Newfoundland Labrador, old-growth forests are valued for their biodiversity and role in climate regulation. Primary old-growth forests, untouched by humans, hold irreplaceable ecological value, while secondary old-growth forests may exhibit recovery resembling primary forests. (Newfoundland Labrador Government, n.d).

Finally, some provinces and territories, such as Ontario, Yukon, Northwest Territories, Saskatchewan, and Prince Edward Island, lack specific definitions and may refer to primary forests as untouched forests or old-growth depending on the document.

3 MAPPING CANADIAN PRIMARY FORESTS BASED ON ESSENTIAL CRITERIA

Based on the literature review of primary forest definitions and other ancillary terms presented above, we next identify common concepts and criteria used to distinguish primary forests across these definitions and secondly assess their operationalizability in a geospatial workflow map primary forests in Canada. Below we present the summary of this exercise, but the full table of concepts and criteria can be consulted in Annex I and potential datasets in Annex II.

3.1 KEY CONCEPTS AND CRITERIA TO DEFINE PRIMARY FORESTS

From 9 well-established definitions of primary forests and 10 definitions of old-growth, virgin and secondary forests (see Annex I), we have identified 15 concepts and criteria used in the literature to define primary forests and distinguish them from other key forest types. **Error! Reference source not found.** provides a visualization of the frequency of occurrence of each criterion in reviewed definitions by forest type. Criteria common to most definitions of primary forest in the literature include lack of anthropogenic disturbances – particularly recent or major events, native species composition and natural regeneration cycle, as well as lack of visible signs of anthropogenic disturbance or any disturbance ever, though to a lesser degree. Other criteria were less frequently cited or also used to define other forest types. Below we provide a summary of each criterion and their interpretation within the context of Canada's primary forests, with a consensus of the definition of the criteria across multiple occurrences, how consistently it

is used to describe primary forest, its limitations and potential ambiguities and whether it is easily operationalizable.

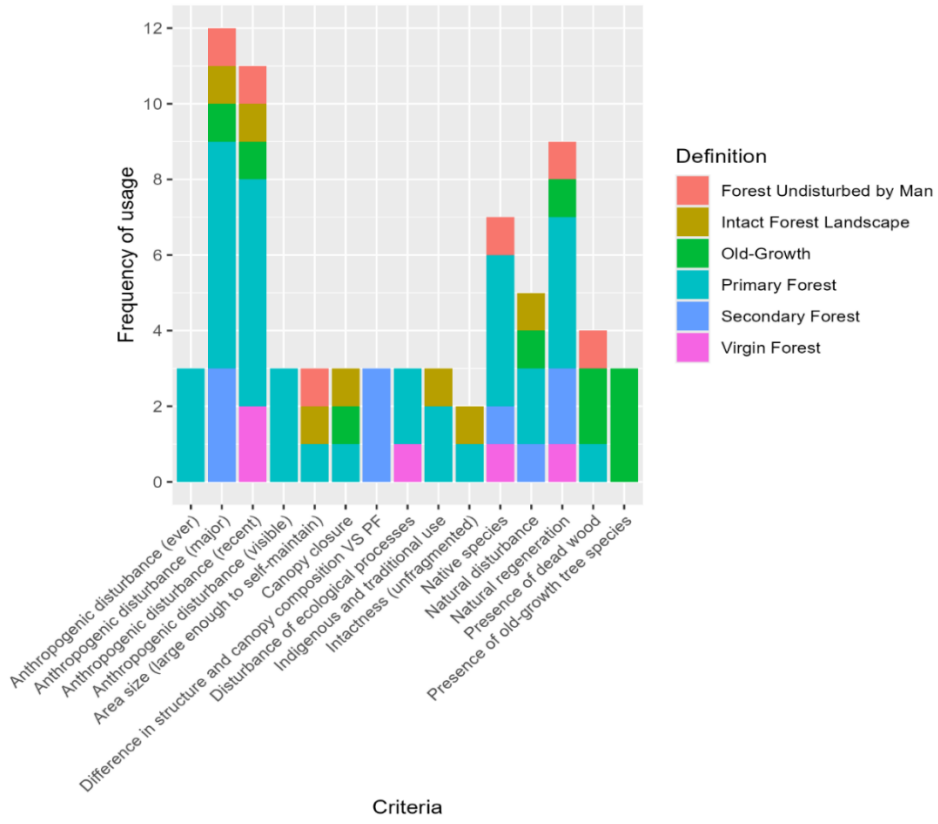

Figure 4. Frequency and distribution of each criterion according to the 19 definitions identified throughout the review of the literature.

Anthropogenic disturbance (ever):

- **Definition:** The absence of human-made disturbance such as timber harvest, land-use change, and large fires. Section 2.1.2 of this review goes further in detail on how large-scale anthropogenic disturbance can impact an ecosystem even over decades and centuries.
- **Consistency:** While it is only used explicitly in 3 of the 9 definitions of primary forests identified for this review, making its consistency relatively low, the definition of this criterion is such that its use also implies that the three following criterion (no major, recent or fine-scale anthropogenic criteria) are also used, which makes it a very strong and consistent – although difficult to operationalize – criterion.
- **Potential ambiguities**: Non-ambiguous, this criterion does not seem to be used for defining other forest types.
- **Limitations**: Some definitions are more radical than others, with some failing to set apart disturbances caused by traditional and indigenous land-use from large-scale timber extraction.

The heterogeneity and potential lack of historical land cover data across Canada makes this criterion difficult to operationalize.

Anthropogenic disturbance (major):

- **Definition**: Understood as the absence of stand-replacing human-made disturbance. This has been the most frequently identified criterion throughout this review. This criterion implies that anthropogenic disturbances can vary in magnitude, with some definitions highlighting that a primary forest must not have been subject to a "significant" human caused disturbance (FAO, 2018; Forest Europe, 2020). This also implies that low-impact harvest (e.g. firewood, selective harvest, deadwood harvest) does not alter a forest's classification.
- **Consistency**: Medium, used in 6 of the 9 definitions of primary forest listed in this review.
- **Potential ambiguities**: Ambiguous. Other types of forests such as secondary, old-growth forests and forests undisturbed by man are often defined as not showing signs of major human activity or disturbances.
- **Limitations**: There is a significant gap in accessible geospatial data regarding private land allocations and cut blocks in the timber industry. Thus, deforestation for timber purposes needs to be inferred using remote sensing models (see Hermosilla et al, 2018) which do not consider deforestation predating the advent of large-scale remote sensing in the 1980's. Further, the lack of a harmonized national-scale wildfire dataset impedes the mapping of human-induced wildfires (although the Canadian National Fire Database does differentiate natural fires from human-caused, it remains moderately incomplete – see Annex III).

Anthropogenic disturbance (recent):

- **Definition**: The absence of recent anthropogenic disturbances. This is the second most frequent criterion identified in this review.
- **Consistency**: Medium, used in 6 of the 9 definitions of primary forest listed in this review.
- **Potential ambiguities**: Ambiguous. While this criterion allows to distinguish primary from secondary forests, it's also used to define intact forest landscapes, forests undisturbed by man, virgin and old-growth forests.
- **Limitations**: Since forests throughout widely vary in their composition and ecology, apart from Potapov et al. (2017)'s definition of Intact Forest Landscapes, no definitions state a threshold for a disturbance to be regarded as 'recent' – that is, a set number of years since disturbance of a certain growth stage.

Anthropogenic disturbance (visible, fine scale):

- **Definition**: The absence of visible signs suggesting the occurrence of human-made disturbances and other activities.
- **Consistency**: Low, used in 3 of the 9 definitions of primary forest listed in this review.
- **Potential ambiguities**: Ambiguous. This criterion is relatively rarely used but can also allow to identify forests undisturbed by man, that are not necessarily primary forests.
- **Limitations**: The definition of visible, fine-scale signs of disturbance is kept vague, but can be understood as the presence of tree stumps and left-over trees from large-scale harvest practices. Identifying signs of fine-scale human disturbances requires on site surveys and can be difficult to operationalize at large scale. Depending on how vague the definition of "fine scale" is kept, this

criterion can be in direct opposition with another criterion used to identify primary forests: their indigenous and traditional use (see Indigenous and traditional use criterion listed below).

Native species:

- **Definition**: Presence of plant and tree species native to the forest's surrounding area. Broadly overlaps with the concept of "natural species composition" often found in the literature. Invasive species are usually a sign of human intervention (plantations [city parks, sylviculture, mine reclamation] or high-traffic areas such as provincial parks). Few invasive tree species dominate the canopies of Canadian forests – mainly Norway spruce (*Picea abies*), Scotch pine (*Pinus sylvestris*), White mulberry (*Morus alba*) and tree of heaven (*Ailanthus altissima*). The other invasive forest species (some trees, shrubs, ferns, and other vascular plants) rarely, if ever, dominate the canopy. They are numerous and their spatial distribution is not currently kept track of at the federal level.
- **Consistency**: Low, although most of the definitions imply the absence of invasive species by referring to a primary forest as resembling what originally covered a region before human-driven changes in the environment (e.g. Dubois 2005), or as being undisturbed (e.g. SCBD 2001), which could be understood as the absence of non-indigenous species.
- **Potential ambiguities**: Ambiguous. The absence of native species is also often explicitly listed as a criterion to identify old-growth, secondary, or virgin forests.

Limitations: Forest surveys, both federal and sub federal, are not thorough enough to fully account for the absence or presence of non-native species. Remote-sensing based surveys rarely account for the presence of non-native species at the canopy level, and even less so for under-canopy vegetation. In that regard, the National Forest Inventory only accounts for the presence of Norway spruce. Further, one would need to account for species native to Canadian forests that have been pushed out of their pre-modern biogeographical distribution because of human-induced climate change. Considering the current extent of science, the latter seems to be out of reach for the time being.

Natural regeneration:

- **Definition**: Understood as the absence of human interaction at any point in the forest's current regeneration and succession process. This criterion rules out forests that have been directly managed such as selective logging or plantations, including tree planting efforts in the forestry industry. Implies that forests may be of any age if the natural disturbance pattern stayed within "historic bounds".
- **Consistency**: Medium, like other criteria, while natural regeneration is not necessarily explicitly mentioned in some definitions, it is sometimes implicit. For example, the absence of human intervention implies that regeneration must happen naturally
- **Potential ambiguities**: Ambiguous, this criterion is often used to characterize other types of forests (old growth, etc).
- **Limitations**: There is no federal or sub-federal geospatial dataset representing planted forests, nor modelized dataset produced on the matter.

Natural disturbance:

- **Definition**: This criterion refers to an ecosystem wherein ecological dynamics are primarily driven by natural disturbance regimes. In Canada, natural disturbances regimes refer to wildfire patterns, endemic insect outbreaks that result in large scale defoliation events, windthrow, ice storms, etc. In the context of Canada's primary forests, special attention should be given to this criterion. Wildfires are the main natural disturbance dynamics of boreal forests, and have been since the last glacial maximum, while pest outbreaks and windthrows are common natural disturbances in temperate forests. If the stated end goal of creating a definition of Canada's primary forests is to highlight their naturalness and the absence of man-made impacts on their ecology, it should be designed in a way that does not discriminate primary boreal forests based on the occurrence of natural, stand replacing forest fires.
- **Consistency**: This criterion was only mentioned once within the context of primary forests (Kormos et al., 2018), yet is referenced often throughout the literature when writing about "natural forest dynamics" and "ecological processes". This further implies that stand age is not relevant in the definition of primary forests as no piece of literature (grey or academic) states that primary forests are defined by an absence of natural disturbances rather than their "normal" occurrence.
- **Potential ambiguities**: Ambiguous. Natural disturbances can occur in all types of forests and is even used as a criterion in some definitions of old growth and secondary forests, as well as intact forest landscapes.
- **Limitations**: Inherently hard to distinguish naturally occuring disturbances from those resulting from human interaction, weather directly or through climate forcing.
- **Operationalization:** The occurrence of naturally occurring natural disturbances should be inclusive to the definition. On the other hand, the occurrence of non-naturally occurring disturbances should be exclusive to the definition. Keeping this in mind, it could be argued that since complete datasets representing historical forest fires in Canada only go back to the 1980's (Hermosilla et al., 2016; Wulder et al., 2024), most wildfires appearing in those datasets that occurred in temperate ecozones fell outside of the historical range of probability (i.e. they are most likely of anthropogenic origin, through direct or undirect channels). This criterion could be made operationalizable by excluding from the selection forest patches that were affected by wildfires in the temperate forest regions (i.e. the Atlantic maritime, Mixedwood plains, prairies and Pacific maritime ecozones). The reasoning behind this method would be that while forest fires may naturally occur in those areas – mostly on a few, select stands – they do not represent the main disturbance dynamic (Fischer et al., 2013; Sanborn et al., 2006).

Disturbance of ecological processes:

- **Definition**: Undisturbed ecological processes such as species interaction, ecosystemic functions, disturbance patterns and other dynamics operating at various spatial and temporal scales. The potentially large spatial scale of this criterion (e.g. changes in time since disturbance on a regional level, wildfire suppression…) suggests that modelized indices of human impact could be suitable for its operationalization. Anthropogenic pressure (human footprint or modelisation of ecosystem integrity) could serve as a proxy for certain sources of disturbance of ecological processes, such as water pollution or edge affects around settlements. Buffers around anthropogenic features could represent
- **Consistency**: This is a very broad criterion that encompasses most of the other criteria found here.

- **Potential ambiguities**: For the same reason, it is also a potentially ambiguous criterion.
- **Limitations**: Small scale disturbance remains relatively unmappable and only approximative. Disturbances working in more diffuse methods such as climate forcing, changes in precipitation patterns, or the migration of forest species due to global warming remain unmappable.

Area size (large enough to self-maintain):

Definition: Small forested areas, even if historically unaffected by humans, might still be too small to self-maintain (regenerate and maintain itself under natural, baseline conditions). Area size should technically vary depending on ecozone. The definition of Intact Forest Landscapes sets 50 MH as a minimal area threshold, although it should be noted that they differ in definition from the other definitions of primary forests (Lee, 2003; Potapov et al., 2017). As seen in works pertaining to Intact Forest Landscapes, there should be a way to exclude (or at least to label differently) thin strips of primary forests too small to self-maintain.

- **Consistency**: Low, only mentioned once within the context of primary forests (FAO, 2018). Although, some other criterion such as intactness and the maintenance of natural processes imply that a forest must have a sufficient size and be unfragmented.
- **Potential ambiguities**: In our review, only intact forest landscapes use this criterion explicitly.
- **Limitations**: Could prove problematic if trying to identify small primary forests patches surrounded by naturally treeless areas such as wetlands, tundra and prairies.

Indigenous and traditional use:

- **Definition**: Some definitions specifically highlight the potential for forests having undergone traditional use by Indigenous people to still be considered as primary. The spirit of this criterion is to acknowledge that the traditional use by Indigenous people – including, but not limited to, spiritual use, agroforestry, firewood gathering, hunting and fishing practices – strongly differs from the practices that came from settling and large-scale timber harvest.
- **Consistency**: Low, only two definitions explicitly acknowledge this use.
- **Potential ambiguities**: Ambiguous, while not necessarily mentioned in definition of other forest types, all other types of forest may potentially display signs of indigenous and traditional use.
- **Limitations**: Limited data on current and historical indigenous land use hinders the accurate inclusion of indigenous perspectives in defining primary forests in Canada, making increased research and collaboration with indigenous communities essential.

Canopy closure:

- **Definition**: Sometimes referenced as crown closure. Aims to discriminate sparsely forested areas without a continuous tree cover.
- **Consistency**: Low, this criterion is only explicitly used in one definition of primary forest (Kormos et al., 2019).
- **Potential ambiguities**: Ambiguous, other types of forest may have the same canopy cover as a primary forest.
- **Limitations**: For the purpose of the FAO and the Canadian National Forestry Inventory, an area is considered treed if the crown closure is at least 10%. This could prove problematic during operationalization, since forest patches that have underwent a recent naturally occurring stand replacing fire – or possibly any other kind of natural disturbance, even non replacing – could have

a low canopy closure percentage. One should note that the climax canopy closure percentage varies depending on forest region, stand type and tree successional pathways, with northern boreal forest stands often having a crown closure that falls under 10% (Mackey, et al., 2021). In short, there is a lack of datasets that fully represent forest extent, the canopy closure percentage of each stand, and that includes temporarily unforested land for Canada.

Intactness (unfragmented):

- **Definition**: Absence of roads, forest roads, navigable rivers, powerlines, and pipelines cutting through a forest. Broadly overlaps with the area size criterion, as both aim to represent a forest's ability to self-maintain, as well as with the disturbance of ecological process criterion. An unfragmented forest allows for maximum connectivity and movement of both animal and plant species. This criterion is highly operationalizable in nature (see Potapov et al. (2017) and their definition of Intact Forest Landscapes) and allows for the exclusion of thin strips of forests or patches with low compactness ratio, for instance. Forest patches directly adjacent to any fragmenting feature will see their intactness and ecological integrity affected. Thus, adding buffer zones surrounding fragmenting features should be required to operationalize this criterion. The large swath of studies pertaining to the woodland caribou (Barber et al., 2018; Venier et al., 2014; Vors et al., 2007), combined with its precise habitat requirements and its near-pan-Canadian distribution, means that this species could serve as a proxy for quantifying the buffer distances that should surround anthropogenic features, as seen in Venier et al. (2022)'s analysis of size threshold for Canadian intact forest landscapes.
- **Consistency**: Medium. intactness is only cited in Kormos's (2018) definition of primary forests, and only implicitly, by listing the absence of road and dam construction along other potential human disturbances. Otherwise, the concept is widely used amongst the literature focused on mapping deforestation (Potapov et al., 2017; Turubanova et al., 2018; Venier et al., 2018).
- **Potential ambiguities**: Potentially ambiguous, this is also an important criteria of intact forest landscapes, which are not incompatible with primary forests.
- **Limitations**: Absence of thorough geospatial data on forest roads at the federal and sub federal levels. Across Canada's forests, forest roads both old and new fragment ecosystems and impede on the dispersal of species.

3.2 PROPOSAL FOR AN OPERATIONALIZABLE DEFINITION

3.2.1 Recent mapping efforts of primary forests

Although the concept of primary forests has generated a large amount of discussion – and especially so at the turning of the century (Buchwald, 2005; Chokkalingam & De Jong, 2001; Dubois, 2005; Mosseler et al., 2003) – few mapping efforts have been attempted. Today, with the growing democratization of GIS, remote sensing tools, and with increasing access to (recent) historical records, more projects tackle the challenge of mapping primary forests.

Sabatini et al. (2021) have recently created a geospatial database of Europe's primary forests. They follow the spirit of FAO's definition of primary forests from 2018, specifically mapping:

"Relatively intact forests that have always or at least for the past sixty to eighty years been essentially unmodified by human activity. [Where] human impacts […] have been limited to low levels of hunting, fishing and harvesting of forest products, and, in some cases, to historical or pre-historical low intensity agriculture. An umbrella term containing Primeval forests, Virgins forests, Old-growth forests, among others. " (FAO, 2018)

Given that the FAO's definition encompasses most of the criteria found in other definitions the methods used to map Europe's primary forests are highly relevant to generating an operationalizable definition of Canada's primary forests. While Europe is about as large as Canada, it is considerably less forested, more densely populated, and a large part of its forests are managed and/or under good data coverage. As a result, Sabatini et al. (2021) followed an additive method, whereby government institutions and researchers were directly queried to add their own geospatial data – both polygons and point data – to the dataset, to provide detailed data on the forest areas which best represented the primary forest definition.

Other efforts have focused on mapping primary forest in the humid tropics (such as Turubanova et al. (2018)) for forests in three tropical countries – Brazil, the DRC and Indonesia. Their definition of primary humid tropical forests is based on the definition of Intact Forest Landscapes (IFL) seen in Lee (2003) and Potapov et al. (2017), and excludes forests that have been visibly affected by stand-replacing disturbances, even if non-anthropogenic. The data coverage and spatial reality of those countries are closer to Canada's, and thus allow for a subtractive method based on remote sensing, whereby forest stands are successive removed from the map using exclusion criteria. In their method, Turubanova et al (2018) first map their study areas' primary forests using historical remote sensing data from 2001. To identify their extent, they use classification methods which consider local variability (species composition), the typical primary forest spectral signature and texture, and exclude younger (non-mature) forest patches. They then subtract from the result's extent the global forest loss data since 2000 (Hansen et al., 2013). While Turubanova et al. 2018's method is highly operationalizable, their definition of primary forests is much narrower, as it is tailored to the realities encountered in tropical countries where forestry and land-use change is prevalent.

In Canada, there have been limited efforts to map primary forests. In 2021, the organization Conservation North has published an online map of British Columbia's primary forests which was recently updated (Conservation North, 2023). This is, to our knowledge, the only map representing primary forests within Canada. Their definition differs from the others, identifying primary forests as: "*Forest of any age that has never been industrially logged. It includes natural forests recently disturbed by wildfire, wind or insects.*"

Again, their operationalization method is subtractive – after identifying forest extent within British Columbia, they subtract provincial cutblock data (i.e. land concessions for forestry), anthropic markers (roads, pipelines, mines, and powerlines) and finally remote-sensing derived data on recent (1985-2020) Canadian forest harvest. This last piece of data is a medium resolution (30m) data inferring forest harvest for each year between 1985 and 2020, and falls under the umbrella of Government of Canada's National Forest Inventory Service (Hermosilla et al., 2016).

3.2.2 An operationalizable definition to map primary forests in Canada

The criteria detailed above help narrow down what could be understood as a primary forest in the context of Canada according to recent science and policies established by NGOs, various level of government as

well as academia. Considering this, as well as the need for a definition that is both operationalizable and that is in accordance with the different ecologies of Canada's forests, we propose a definition for Canadian primary forests below as

- **"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 recent or major anthropogenic disturbances or usage other than traditional land use.**"
- *Forests with at least 5% canopy cover*: canopy closure was only used in one definition of primary forest (Kormos et al., 2018), but it is important to define what is to be considered as a sufficient canopy cover or closure in the Canadian context, where forest are often sparser than in other climates, due to harsh conditions and an abundance of wetlands. As cited above, datasets identifying forests globally usually use a larger threshold for canopy cover. Defining a Canadian-specific threshold will make identifying primary forest in Canada more accurate.
- *Of any age class*: Across the different definition, there does not appear to be a strong argument made for restricting primary forest by a certain age class. This is also consistent with the potential fire regime in boreal primary forests, that would make it so the age of primary forests would vary.
- *Composed of naturally regenerated native species*: this criterion tackles the fact that the natural age structure and composition are important criteria identified in the literature, that make a forest resemble their original historic state. Only citing the natural regeneration and composition (native species) still implies that a forest has a natural age structure (through natural regeneration).
- *Undergoing natural ecological processes:* While this criterion is not necessarily easy to operationalize due to the lack of clarity surrounding what a "natural ecological process" is, and the difficulty for some to track them remotely or at certain scales (e.g. finer scale species interactions) this must be kept in mind as the disturbance of some processes such as the loss of some species interaction or a change in primary productivity might be warning signs of a forest disturbance. This criteria also implies that the size and intactness of a forest are sufficient to maintain said processes, and thus implies the area size and intactness criterion.
- *Subjected to natural forest disturbance dynamics:* While this criterion is not often cited in the literature, it is especially important in the Canadian context, as explained in section 3.1, given the importance of the fire regime for the maintenance of primary boreal forests.
- *Not recently impacted by anthropogenic disturbances or usage:* Among the four criteria citing the absence of anthropogenic disturbance (ever, major, recent, fine scale), we chose to only restrict primary forest to forests that have not been recently disturbed. The reason behind this choice is that it is not possible to easily know whether a forest has ever been disturbed, other than if the natural processes were shifted toward another type of forest, which would then be caught by other criteria.
- *Other than traditional land use:* Traditional and indigenous land use does not significantly disturb the dynamics and processes of a landscape and as such should not be included in broader, more industrial, anthropogenic disturbances.

To have a definition across Canadian forest that is operationalizable, several concepts and criteria identified in section 3.1 and Annex I were dropped. These criteria were either specific for a certain forest type (for instance “Presence of lichens” in old-growth forest) or could be amalgamated with another criterion (as was done with “Natural age structure”, which was amalgamated with "Natural regeneration”).

To apply this definition across the varied forest of Canada, and given data limitations, certain criteria should be applied differently across forested ecozones. Specifically, considering the absence of thorough datasets related to historical wildfires (both anthropogenic and natural) and the absence of wildfire as an ecosystem-defining disturbance regime in Canada's temperate and humid forests, we consider any fire happening in the Atlantic Maritime, Mixedwood Plains, Prairies, and Pacific Maritime ecozones as being anthropogenic either through direct ignition or through climate forcing.

To account for the most sparsely populated stands in the taiga ecozones, a forest patch would be considered forested if at least 5% canopy cover is reached. Forest patches that burnt within the past 30 years have no minimum canopy cover threshold. Following the literature on intact forest landscapes (Lee, 2003; Potapov et al., 2017; Turubanova et al., 2018), we propose to subdivide primary forests in three categories according to their patch size:

- Patches that fit in the above definition of primary forest with an area larger than 50,000 hectares are considered as “primary forest landscapes”;
- Similarly, those forests smaller than 50,000 hectares but larger than 1,000 hectares are considered as “primary forests”;
- Those smaller than 1,000 hectares, and/or forest appendages/corridors with a width smaller than 500 meters, are considered as “primary forest fragments”.

In addition to the above criteria, additional thresholds can be applied to mapped primary forest to better understand their potential role in supporting fauna biodiversity:

Patch size thresholds: Following Vernier’s (2022) work, patch size thresholds could vary depending on ecozones (or Homogenous Fire Regime Zone) – the goal here is to exclude forests too small to be self-sufficient. Another way to quantify minimal patch thresholds needed for resilience would be to multiply the mean patch size of the primary disturbance type by Lee (2003). Communities other than trees and certain mammals rarely need a patch size larger than a dozen hectares to achieve resilience and self-maintenance (Gignac & Dale, 2007; Hobson & Bayne, 2000; Pyper, 2010; Venier et al., 2018).

Minimum width of appendages and corridors: Throughout Canada’s forests, studies show that animal biodiversity can be maintained in very thin strips of forest (<500 meters) (Hannon et al., 2002; Shirley, 2002). While considering edge effects as a proxy to the self-maintenance of thin strips of forests, tree species, lichen and under canopy vegetation are mainly unaffected past 200 meters (Baltzer et al., 2014; Burton, 2002; Harper et al., 2015; Kremsater & Bunnell, 1999; Rheault et al., 2003). However, it should be noted that this does not account for the capacity of certain species to regenerate within the site after a stand replacing disturbance (e.g. in the absence of neighboring stands of the same taxon) – or reproduce, in the case of animals.

Buffer around human infrastructure: As stated in section 3.1, the woodland caribou makes for a good proxy of human impact on forests. The exact distance of impact varies amongst the experts (Barber et al., 2018; Venier et al., 2014; Vors et al., 2007), but we choose to follow Venier et al. (2014) for the buffer

zone sizes. Based on literature on woodland caribou, which is strongly associated with primary forests, we suggest that the species is strongly affected by anthropogenic land uses. According to Vernier (2014, 2022) forest patches located within 1 km of low-use roads, pipelines and powerlines, 2 km of high-use roads and underground mines, 9 km of towns and urban zones, and 14 km of open-pit mining and other major infrastructures should be excluded from being classified as primary forests

3.3 MAPPING CANADA'S PRIMARY FORESTS

3.3.1 Datasets

We undertook an extensive review of available datasets to map primary forests in Canada. This included both government-produced datasets and those produced by research groups in the scientific literature that are available at the national at the scale of Canada. A full list of these datasets considered is available in Annex III.

The datasets that we chose to use in our proposed workflow to identify primary forests are marked as such in the column '*Used in operationalization'*. The other datasets are either of general interest to our review of the literature or are complementary to the operationalization. As certain columns did not fit this document, a full version of the table in Annex III can be found attached to this document in WWF_Definition-Characteristics-Operationalization.xlsx.

3.3.2 Operationalization

We outline a step-by-step method to mapping of primary forests that corresponds to our proposed, operationalizable, definition of primary forests. This method is depicted as flowchart gives information detailing the datasets that could be used and how to use them in a subtractive fashion (see attached file operationalization_workflow.pdf), and the possible outputs (primary forest, landscapes and fragments).

3.3.3 Feasibility and limitations

Choosing the appropriate forest extent dataset to initiate the method is a potential barrier to the operationalization of our definition of primary forests. While very thorough, the National Forest Inventory (Wulder et al., 2024) uses the FAO's definition of a forest which excludes patches of forest with <10% canopy cover and <5m height. This excludes a significant portion of forests in Taiga ecozones. However, their dataset does account for temporarily unforested land, either through fire or deforestation. We chose to use the forest extent dataset produced by GLAD, now located in the recently updated Global Forest Loss dataset (Hansen et al., 2013). Although it does not seem to include temporarily unforested land, their forest extent layer includes any cell that has >1 canopy cover and >=3m height. However, forest patches lower than 3m are still excluded. One should keep in mind that temporarily unforested land accounts for 4.9% of forested area (Wulder et al., 2024).

Regarding the absence of non-native species criteria, no datasets accurately report the presence of invasives, other than when they are observed at canopy level. Thus, other than when using sub-federal

level tree inventories – which sometimes incorporate some form of field-based validation, as with Québec's IEQM4 dataset – the presence of sub-canopy invasives is unaccounted for.

Further, while the criteria regarding the exclusion of planted forests (i.e. non-naturally regenerated forests) is crucial to our proposed definition of primary forest as well as most definitions surveilled over this review, we find that there are no datasets accurately representing tree plantations in Canada.

With regards to wildfires and anthropogenic fires, the twelve forested ecozones used in discriminating the former from the latter could be swapped for Boulanger's homogenous fire regime zones (Boulanger et al., 2014) to obtain better granularity on fire regimes operating within ecozones. For instance, the eastern part of the Boreal shield ecozone roughly contains three homogenous fire regime zones that greatly differ in fuel load, annual area burned and fire occurrence.

It is inherently impossible to accurately map historical anthropological disturbances at the scale of Canada. However, as noted in section 2.1.2, the legacies of human disturbances on forests can be empirically observed centuries after. After careful consideration of the literature, we believe that restricting the anthropological disturbance criteria to only include "recent disturbances" would go against the spirit of the concept of a primary forest is. Thus, we suggest excluding any forest that has been disturbed by humans – save for traditional indigenous use – as far as the available data allows.

Moreover, understanding current and historical indigenous land use poses significant challenges due to limited available data, hindering the accurate incorporation of indigenous realities and knowledge into operational definitions of primary forest in Canada. This lack of comprehensive data complicates efforts to fully capture and respect indigenous perspectives within broader definitions and frameworks. Addressing these knowledge gaps through increased research and collaboration with indigenous communities would be essential to fostering a more inclusive and accurate portrayal of primary forests and indigenous realities in Canada.

Further understanding the behavior of animals other than the woodland caribou vis-à-vis anthropic infrastructure and fragmentation features could help detail the operationalization. Species could be chosen for each ecozone as a proxy of human impact to fine-tune the buffers.

Lastly, we note that there is no data currently available for forest roads at the scale of Canada, though they are available for some provinces (e.g. Québec). They are omnipresent source of disturbance in northern Canadian forests and thus are highly relevant to this mapping exercise. Having accurate data regarding their localization is crucial to further detail the buffers surrounding low-use roads. As detailed in section 3.2, edge effects should be considered in the operationalization.

4. CONCLUSION

Mapping Canada's primary forests is a multifaceted endeavor shaped by diverse ecological landscapes and varying definitions in global literature. This study synthesized critical criteria from international and national primary forest definitions and proposed an operationalizable framework tailored to the complexities of Canadian forests. Key criteria identified include the absence of recent anthropogenic disturbances, native species composition, natural regeneration processes, and intact ecological dynamics. These criteria were selected for their applicability across Canada's diverse forested regions, considering the variability in ecological conditions and data availability.

Mapping efforts for Canadian primary forests have been historically limited but are advancing with the evolution of Geographic Information Systems (GIS) and remote sensing technologies. Lessons from methodologies applied in Europe and tropical regions offer valuable insights into operational approaches, particularly in using subtractive mapping techniques based on exclusion criteria such as recent logging activities and infrastructure presence. Adapting these methods to Canada requires careful consideration of unique ecological factors and comprehensive spatial data coverage.

The proposed definition categorizes primary forests into distinct categories—landscapes, forests, and fragments—based on size thresholds and ecological integrity. This tiered approach accommodates the diversity of forest types and disturbance regimes found across Canada, aiming to safeguard biodiversity and ecosystem functions by identifying and protecting intact forest areas essential for ecological resilience.

Significant major challenges persist, including data deficiencies in monitoring non-native species, historical logging practices, and understanding the historical impacts of indigenous land use practices. While multiple criteria remain functionally unmappable, some can be operationalized using global models. The lack of intergovernmental coordination in data harmonization remains a significant issue and results in the absence of certain key geospatial datasets (eg. Forest roads, cut blocks, forest extent and inventories). Addressing these gaps through enhanced data collection methodologies and meaningful engagement with indigenous communities is crucial for refining and implementing an effective primary forest mapping framework. Furthermore, ongoing research efforts are necessary to deepen our understanding of how anthropogenic features impact forest ecosystems and to refine buffer zone recommendations around such features.

Finaly, while mapping Canada's primary forests poses both technical and conceptual challenges, the proposed framework provides a robust foundation for future conservation efforts. By integrating ecological principles with advanced mapping techniques, Canada can effectively manage and conserve its diverse primary forest ecosystems, ensuring their resilience and sustainability for future generations. This approach underscores the importance of collaborative efforts among stakeholders, researchers, and policymakers to achieve comprehensive and accurate mapping of Canada's primary forests.

REFERENCES

Baguette, M., Blanchet, S., Legrand, D., Stevens, V. M., & Turlure, C. (2013). Individual dispersal, landscape connectivity and ecological networks. *Biological Reviews*, *88*(2), 310–326. https://doi.org/10.1111/brv.12000

Baltzer, J. L., Veness, T., Chasmer, L. E., Sniderhan, A. E., & Quinton, W. L. (2014). Forests on thawing permafrost: Fragmentation, edge effects, and net forest loss. *Global Change Biology*, *20*(3), 824–834. https://doi.org/10.1111/gcb.12349

Barber, Q. E., Parisien, M.-A., Whitman, E., Stralberg, D., Johnson, C. J., St-Laurent, M.-H., DeLancey, E. R., Price, D. T., Arseneault, D., Wang, X., & Flannigan, M. D. (2018). Potential impacts of climate change on the habitat of boreal woodland caribou. *Ecosphere*, *9*(10), e02472. https://doi.org/10.1002/ecs2.2472

Barredo, J., L., Brailescu, C., Teller, A., Sabatini, F. M., Mauri, A., & Janouskova, K. (2021). *Mapping and assessment of primary and old-growth forests in Europe*.

Bergeron, Y., & Fenton, N. J. (2012). Boreal forests of eastern Canada revisited: Old growth, nonfire disturbances, forest succession, and biodiversity. *Botany*, *90*(6), 509–523. https://doi.org/10.1139/b2012-034

Boulanger, Y., Gauthier, S., & Burton, P. J. (2014). A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Canadian Journal of Forest Research*, *44*(4), 365–376. https://doi.org/10.1139/cjfr-2013-0372

British Colombia Government. (n.d.). *Old growth definitions and values—Province of British Columbia*. Province of British Columbia. Retrieved June 3, 2024, from https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/old-growth-forests/old-growth-values

Buchwald, E. (2005). *A hierarchical terminology for more or less natural forests in relation to sustainable management and biodiversity conservation*. *11–19*, 111–127. https://forestsandco.wordpress.com/wp-content/uploads/2015/11/buchwald_2002_definitions.pdf

Burton, P. (2002). Effects of clearcut edges on trees in the sub-boreal spruce zone of Northwest-Central British Columbia. *Silva Fennica*, *36*(1). https://doi.org/10.14214/sf.566

Chokkalingam, U., & De Jong, W. (2001). Secondary forest: A working definition and typology. *International Forestry Review*, *3*(1), 19–25.

Conservation North. (2023). *Seeing Red v 2.0: BC's last primary forests* [Online map]. https://www.arcgis.com/apps/webappviewer/index.html?id=d1620f43f9084a99a4921e5e8b9b98dd

Coogan, S. C. P., Daniels, L. D., Boychuk, D., Burton, P. J., Flannigan, M. D., Gauthier, S., Kafka, V., Park, J. S., & Wotton, B. M. (2021). Fifty years of wildland fire science in Canada. *Canadian Journal of Forest Research*, *51*(2), 283–302. https://doi.org/10.1139/cjfr-2020-0314

DeSantis, R. D., Hallgren, S. W., & Stahle, D. W. (2011). Drought and fire suppression lead to rapid forest composition change in a forest-prairie ecotone. *Forest Ecology and Management*, *261*(11), 1833–1840. https://doi.org/10.1016/j.foreco.2011.02.006

Dubois, F. (2005). *La déforestation des forêts primaires dans le monde: États des lieux, risques connus, approches de solutions.* [Master's thesis, École nationale supérieure des sciences de l'information et des bibliothèques]. http://enssibal.enssib.fr/bibliotheque/documents/dessride/rrbdubois.pdf

European Environment Agency. (n.d.). *Term: Old-Growth forests* [Glossary]. European Environment Agency. Retrieved July 30, 2024, from https://www.eea.europa.eu/help/glossary/eea-glossary/old-growth-forest

FAO. (2018). *Global Forest Resources Assessment 2020: Terms and Definitions* (Forest Resources Assessment Working Paper 188). FAO (Food and Agriculture Organization of the United Nations). https://openknowledge.fao.org/server/api/core/bitstreams/531a9e1b-596d-4b07-b9fd-3103fb4d0e72/content

Fischer, A., Marshall, P., & Camp, A. (2013). Disturbances in deciduous temperate forest ecosystems of the northern hemisphere: Their effects on both recent and future forest development. *Biodiversity and Conservation*, *22*(9), 1863–1893. https://doi.org/10.1007/s10531-013-0525-1

Forest Europe. (2020). *State of Europe's Forests 2020*. Ministerial Conference on the Protection of Forests in Europe. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. Z., & Schepaschenko, D. G. (2015). Boreal forest health and global change. *Science*, *349*(6250), 819–822. https://doi.org/10.1126/science.aaa9092

Gignac, L. D., & Dale, M. R. T. (2007). Effects of size, shape, and edge on vegetation in remnants of the upland boreal mixed-wood forest in agro-environments of Alberta, Canada. *Canadian Journal of Botany*, *85*(3), 273–284. https://doi.org/10.1139/B07-018

Government of Canada. (n.d.). *The State of Canada's Forests: Annual Report 2023* [Annual report]. Natural Resources Canada. https://publications.gc.ca/collections/collection_2024/rncan-nrcan/Fo1-6-2023-eng.pdf

Grondin, P., Gauthier, S., Poirier, V., Tardif, P., Boucher, Y., & Bergeron, Y. (2018). Have some landscapes in the eastern Canadian boreal forest moved beyond their natural range of variability? *Forest Ecosystems*, *5*(1), 30. https://doi.org/10.1186/s40663-018-0148-9

Hanes, C. C., Wang, X., Jain, P., Parisien, M.-A., Little, J. M., & Flannigan, M. D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, *49*(3), 256–269. https://doi.org/10.1139/cjfr-2018-0293

Hannon, S. J., Paszkowski, C. A., Boutin, S., DeGroot, J., Macdonald, S. E., Wheatley, M., & Eaton, B. R. (2002). Abundance and species composition of amphibians, small mammals, and songbirds in riparian forest buffer strips of varying widths in the boreal mixedwood of Alberta. *Canadian Journal of Forest Research*, *32*(10), 1784–1800. https://doi.org/10.1139/x02-092

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, *342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Harper, K. A., Macdonald, S. E., Mayerhofer, M. S., Biswas, S. R., Esseen, P., Hylander, K., Stewart, K. J., Mallik, A. U., Drapeau, P., Jonsson, B., Lesieur, D., Kouki, J., & Bergeron, Y. (2015). Edge influence on vegetation at natural and anthropogenic edges of boreal forests in \textlessspan style="font-variant:small-caps;"\textgreaterC\textless/span\textgreater anada and \textlessspan style="font-variant:small-caps;"\textgreaterF\textless/span\textgreater ennoscandia. *Journal of Ecology*, *103*(3), 550–562. https://doi.org/10.1111/1365-2745.12398

Hennebelle, A., Grondin, P., Aleman, J. C., Ali, A. A., Bergeron, Y., Borcard, D., & Blarquez, O. (2018). Using paleoecology to improve reference conditions for ecosystem-based management in western spruce-moss

subdomain of Québec. *Forest Ecology and Management*, *430*, 157–165. https://doi.org/10.1016/j.foreco.2018.08.007

Hermosilla, T., Wulder, M. A., White, J. C., Coops, N. C., Hobart, G. W., & Campbell, L. B. (2016). Mass data processing of time series Landsat imagery: Pixels to data products for forest monitoring. *International Journal of Digital Earth*, *9*(11), 1035–1054. https://doi.org/10.1080/17538947.2016.1187673

Higgs, E., Falk, D. A., Guerrini, A., Hall, M., Harris, J., Hobbs, R. J., Jackson, S. T., Rhemtulla, J. M., & Throop, W. (2014). The changing role of history in restoration ecology. *Frontiers in Ecology and the Environment*, *12*(9), 499–506. https://doi.org/10.1890/110267

Hobson, K. A., & Bayne, E. (2000). EFFECTS OF FOREST FRAGMENTATION BY AGRICULTURE ON AVIAN COMMUNITIES IN THE SOUTHERN BOREAL MIXEDWOODS OF WESTERN CANADA. *The Wilson Bulletin*, *112*(3), 373–387. https://doi.org/10.1676/0043-5643(2000)112[0373:EOFFBA]2.0.CO;2

Issekutz, P. B. (2020). *A Critical Evaluation of Old-Growth Forest Definitions in Canada*. Dalhousie University.

Jiang, Y., Zhuang, Q., Flannigan, M. D., & Little, J. M. (2009). Characterization of wildfire regimes in Canadian boreal terrestrial ecosystems. *International Journal of Wildland Fire*, *18*(8), 992. https://doi.org/10.1071/WF08096

Kormos, C. F., Mackey, B., DellaSala, D. A., Kumpe, N., Jaeger, T., Mittermeier, R. A., & Filardi, C. (2018). Primary Forests: Definition, Status and Future Prospects for Global Conservation. In D. A. Dellasala & M. I. Goldstein (Eds.), *Encyclopedia of the Anthropocene* (pp. 31–41). Elsevier. https://doi.org/10.1016/B978-0-12-809665-9.09711-1

Kremsater, L., & Bunnell, F. (1999). Edge effects: Theory, evidence and implications to management of western North American forests. *Forest Fragmentation: Wildlife and Management Implications.*, 117–153.

Lee, P. G. (2003). *Canada's large intact forest landscapes: A report by Global Forest Watch Canada*. Global Forest Watch Canada.

Liu, S., Dong, Y., Deng, L., Liu, Q., Zhao, H., & Dong, S. (2014). Forest fragmentation and landscape connectivity change associated with road network extension and city expansion: A case study in the Lancang River Valley. *Ecological Indicators*, *36*, 160–168. https://doi.org/10.1016/j.ecolind.2013.07.018

Mackey, B., Skinner, E., & Norman, P. (2021). *A review of definitions, data, and methods for country-level assessment and reporting of primary forests* (p. 26) [FAO Discussion paper]. Griffith University. https://www.researchgate.net/profile/Patrick-Norman-3/publication/351464479_A_Review_of_Definitions_Data_and_Methods_for_Country-level_Assessment_and_Reporting_of_Primary_Forest/links/6099d53fa6fdccaebd20a513/A-Review-of-Definitions-Data-and-Methods-for-Country-level-Assessment-and-Reporting-of-Primary-Forest.pdf

Morgan, P., Heyerdahl, E. K., Strand, E. K., Bunting, S. C., Riser Ii, J. P., Abatzoglou, J. T., Nielsen-Pincus, M., & Johnson, M. (2020). Fire and land cover change in the Palouse Prairie–forest ecotone, Washington and Idaho, USA. *Fire Ecology*, *16*(1), 2. https://doi.org/10.1186/s42408-019-0061-9

Mosseler, A., Thompson, I., & Pendrel, B. A. (2003). Overview of old-growth forests in Canada from a science perspective. *Environmental Reviews*, *11*(S1), S1–S7. https://doi.org/10.1139/a03-018

Natural Resources Canada. (2022, September 12). *Statistical data*. https://cfs.nrcan.gc.ca/statsprofile/

Nova Scotia Government. (2021). *Old Growth | novascotia.ca*. https://novascotia.ca/natr/forestry/programs/ecosystems/oldgrowth.asp

Potapov, P., Hansen, M. C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S., & Esipova, E. (2017). The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances*, *3*(1), e1600821. https://doi.org/10.1126/sciadv.1600821

Pyper, M. P. (2010). *Retention patch characteristics and ground dwelling beetle diversity: Implications for natural disturbance-based management*. Library and Archives Canada = Bibliothèque et Archives Canada.

Rheault, H., Drapeau, P., Bergeron, Y., & Esseen, P.-A. (2003). Edge effects on epiphytic lichens in managed black spruce forests of eastern North America. *Canadian Journal of Forest Research*, *33*(1), 23–32. https://doi.org/10.1139/x02-152

Rhemtulla, J. M., Mladenoff, D. J., & Clayton, M. K. (2009). Legacies of historical land use on regional forest composition and structure in Wisconsin, USA (mid-1800s–1930s–2000s). *Ecological Applications*, *19*(4), 1061–1078. https://doi.org/10.1890/08-1453.1

Rogeau, M.-P., Flannigan, M. D., Hawkes, B. C., Parisien, M.-A., & Arthur, R. (2016). Spatial and temporal variations of fire regimes in the Canadian Rocky Mountains and Foothills of southern Alberta. *International Journal of Wildland Fire*, *25*(11), 1117. https://doi.org/10.1071/WF15120

Runkle, J. R. (1985). Disturbance Regimes in Temperate Forests. In *The Ecology of Natural Disturbance and Patch Dynamics* (pp. 17–33). Elsevier. https://doi.org/10.1016/B978-0-12-554520-4.50007-1

Sabatini, F. M., Bluhm, H., Kun, Z., Aksenov, D., Atauri, J. A., Buchwald, E., Burrascano, S., Cateau, E., Diku, A., Duarte, I. M., Fernández López, Á. B., Garbarino, M., Grigoriadis, N., Horváth, F., Keren, S., Kitenberga, M., Kiš, A., Kraut, A., Ibisch, P. L., … Kuemmerle, T. (2021). European primary forest database v2.0. *Scientific Data*, *8*(1), 220. https://doi.org/10.1038/s41597-021-00988-7

Sanborn, P., Geertsema, M., Jull, A. J. T., & Hawkes, B. (2006). Soil and sedimentary charcoal evidence for Holocene forest fires in an inland temperate rainforest, east-central British Columbia, Canada. *The Holocene*, *16*(3), 415–427. https://doi.org/10.1191/0959683606hl937rp

Sass, E. M., D'Amato, A. W., & Foster, D. R. (2018). Lasting legacies of historical clearcutting, wind, and salvage logging on old-growth Tsuga canadensis-Pinus strobus forests. *Forest Ecology and Management*, *419–420*, 31–41. https://doi.org/10.1016/j.foreco.2018.03.012

Seidl, R., Honkaniemi, J., Aakala, T., Aleinikov, A., Angelstam, P., Bouchard, M., Boulanger, Y., Burton, P. J., De Grandpré, L., Gauthier, S., Hansen, W. D., Jepsen, J. U., Jõgiste, K., Kneeshaw, D. D., Kuuluvainen, T., Lisitsyna, O., Makoto, K., Mori, A. S., Pureswaran, D. S., … Senf, C. (2020). Globally consistent climate sensitivity of natural disturbances across boreal and temperate forest ecosystems. *Ecography*, *43*(7), 967–978. https://doi.org/10.1111/ecog.04995

Shirley, S. (2002). *Forest fragmentation and regrowth: Use of riparian and upland forest by birds in managed and unmanaged mature coastal British Columbia rainforest* [PhD Thesis, University of British COlumbia]. https://open.library.ubc.ca/media/stream/pdf/831/1.0090748/2

Turner, N. J. (2020). *Plants, People, and Places: The Roles of Ethnobotany and Ethnoecology in Indigenous Peoples' Land Rights in Canada and Beyond*. McGill-Queen's Press - MQUP.

Turner, N. J., Lepofsky, D., & Deur, D. (2013). Plant Management Systems of British Columbia's First Peoples. *BC Studies: The British Columbian Quarterly*, *179*, Article 179. https://doi.org/10.14288/bcs.v0i179.184112

Turubanova, S., Potapov, P. V., Tyukavina, A., & Hansen, M. C. (2018). Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. *Environmental Research Letters*, *13*(7), 074028. https://doi.org/10.1088/1748-9326/aacd1c

Van Bavel, B., MacDonald, J. P., & Dorough, D. S. (2022). Indigenous Knowledge Systems. In K. De Pryck (Ed.), *A Critical Assessment of the Intergovernmental Panel on Climate Change* (1st ed., pp. 116–125). Cambridge University Press. https://doi.org/10.1017/9781009082099.017

Venier, L. A., Pedlar, J. H., Higgins, K., Lawrence, K., Walton, R., Boulanger, Y., & McKenney, D. W. (2022). Size requirements of intact forest landscapes for effective biodiversity conservation under regional fire regimes and climate change. *Biological Conservation*, *276*, 109790. https://doi.org/10.1016/j.biocon.2022.109790

Venier, L. A., Thompson, I. D., Fleming, R., Malcolm, J., Aubin, I., Trofymow, J. A., Langor, D., Sturrock, R., Patry, C., Outerbridge, R. O., Holmes, S. B., Haeussler, S., De Grandpré, L., Chen, H. Y. H., Bayne, E., Arsenault, A., & Brandt, J. P. (2014). Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. *Environmental Reviews*, *22*(4), 457–490. https://doi.org/10.1139/er-2013-0075

Venier, L. A., Walton, R., Thompson, I. D., Arsenault, A., & Titus, B. D. (2018). A review of the intact forest landscape concept in the Canadian boreal forest: Its history, value, and measurement. *Environmental Reviews*, *26*(4), 369–377. https://doi.org/10.1139/er-2018-0041

Vors, L. S., Schaefer, J. A., Pond, B. A., Rodgers, A. R., & Patterson, B. R. (2007). Woodland Caribou Extirpation and Anthropogenic Landscape Disturbance in Ontario. *The Journal of Wildlife Management*, *71*(4), 1249–1256. https://doi.org/10.2193/2006-263

Wiken, E. B., Gauthier, D., Marshall, I., Lawton, K., & Hirvonen, H. (1996). *A perspective on Canada's ecosystems: An overview of the terretrial and marine ecozones* (Occasional Paper NO. 14; p. 99). Canadian Council on Ecological Areas.

Wirth, C., Messier, C., Bergeron, Y., Frank, D., & Fankhänel, A. (2009). Old-Growth Forest Definitions: A Pragmatic View. In C. Wirth, G. Gleixner, & M. Heimann (Eds.), *Old-Growth Forests* (Vol. 207, pp. 11–33). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-92706-8_2

Wulder, M. A., Hermosilla, T., White, J. C., Bater, C. W., Hobart, G., & Bronson, S. C. (2024). Development and implementation of a stand-level satellite-based forest inventory for Canada. *Forestry: An International Journal of Forest Research*, cpad065. https://doi.org/10.1093/forestry/cpad065

ANNEX I - DEFINITIONS AND CRITERA

TYPE	SOURCES	LOCALISATION	OBJECTIVES OF DEFINITION	DEFINITIONS	CRITERIA
Primary forest	UN FAO, 2018	Europe	Conservation	"Naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities, and the ecological processes are not significantly disturbed. Some key characteristics of primary forests are 1) They show natural forest dynamics, such as natural tree species composition, occurrence of dead wood, natural age structure and natural regeneration processes; 2) The area is large enough to maintain its natural ecological processes; and 3) There has been no known significant human intervention or the last significant human intervention was long enough ago to have allowed the natural species composition and processes to have become re-established."	Native species, anthropogenic disturbance (visible, fine scale / recent / major), disturbance of ecological processes, natural regeneration, dead wood, area size (large enough to self-maintain)
Primary forest	UN Secretariat of the Convention on Biological Diversity, 2001	Worldwide	Conservation	"Primary forests are forests that have never been directly disturbed by humans. Whatever their age, they have developed following natural disturbances and according to natural processes. Forests that are used by indigenous and local communities with traditional lifestyles consistent with the conservation and sustainable."	Anthropogenic disturbance (major/ever), natural regeneration, indigenous and traditional use
Primary forest	Dubois, F. 2005	Academia	Research	"Forest which originally covered a region before changes in the environment were brought about by people"	Anthropogenic disturbance (major/ever)
Primary forest	Buchwald, 2005 (UN FAO)	Worldwide	Conservation	"Relatively intact forests that have always or at least for the past sixty to eighty years been essentially unmodified by human activity. [Where] human impacts […] have been limited to low levels of hunting, fishing and harvesting of forest products, and, in some cases, to historical or pre-historical low intensity agriculture. An umbrella term containing Primeval forests, Virgins forests, Old-growth forests, among others."	Anthropogenic disturbance (major/recent), indigenous and traditional use
Primary forest	Mackey, B. 2015	Worldwide	Conservation and policymaking	"Naturally regenerated forest of native species, where there are no clearly visible indications of human activities and ecological processes are not significantly disrupted."	Native species, anthropogenic disturbance (visible, fine scale/recent), disturbance of ecological processes

TYPE	SOURCES	LOCALISATION	OBJECTIVES OF DEFINITION	DEFINITIONS	CRITERIA
Primary forest	Turubanova et al., 2018	Worldwide	Conservation and research	"Primary forest is defined as mature natural [humid tropical] forest cover that has not been completely cleared and regown in recent history. Our definition of primary forest loss consists of all stand-replacement disturbances […], including many associated with degradation dynamics such as road building, intensive logging and severe fire. [...] Primary forests include those affected by selective logging or other disturbances that may have altered forest composition and structure."	Anthropogenic disturbance (major/recent), natural disturbance (absence of)
Primary forest	Kormos et al., 2018	Worldwide	Conservation	"Primary forest describes natural forest that are: Largely undisturbed by industrial-scale land uses such as logging, mining, human-caused fires, dam, and road construction; the result of ecological and evolutionary processes including the full range of successional stages from new to old forest and with natural disturbance processes operating within historic bounds; more likely to possess the full complement of their evolved, characteristic plant and animal species with few if any exotics; dominated by a largely continuous tree canopy cover; and have unpolluted soil and water."	Anthropogenic disturbance (recent), intactness (unfragmented), natural disturbance, native species, natural regeneration, canopy closure, unpolluted soil and water
Primary forest	Peterlssekutz, 2020	Worldwide	Conservation	"Forests where no commercial or major anthropogenic disturbances have ever occurred."	Anthropogenic disturbance (major/ever)
Primary forest	Barredo, 2021	Europe	Policymaking	"Primary forests are considered relatively intact forests following natural dynamics, are naturally regenerated, composed by native species, and especially, show no indication of human activities."	Natural regeneration, native species, Anthropogenic disturbance (visible, fine-scale/recent)
Old-Growth	Secretariat of the Convention on Biological Diversity, 2001	Worldwide	Conservation	"Old growth forests can be primary or secondary forests. They have reached an age at which the structures and species normally associated with old primary forests of that type have accumulated sufficiently to create a forest ecosystem distinct from any younger age class."	Presence of old-growth (late-successionnal) tree species
Old-Growth	Mosseler et al., 2003	Canada	Policymaking and reserach	NA [List of criteria related to temperate old-growth forests in Canada]	Natural regeneration, dead wood, old growth (late-successionnal) tree species, natural disturbance (absence of), anthropogenic disturbance (major/recent)

TYPE	SOURCES	LOCALISATION	OBJECTIVES OF DEFINITION	DEFINITIONS	CRITERIA
Old-Growth	Issekutz, 2020	Academia	Research	"(1) Presence of certain key old-growth tree species with 30% or more crown closure. (2) Presence of indicator lichens (using a lichen identification chart modelled potentially off established published studies. (3) Presence of large amounts of dead wood, assessed through a combination of visible “Mound topography” on forest floor and complementary methods, such as soil sampling."	Presence of lichens, presence of dead wood, old growth (late-successionnal) tree species with >30% canopy closure, microtopography
Virigin forest	Carpathian convention, 2016	Europe	Policymaking	"Natural forests which have not been influenced directly by human activities in their development and natural forest means forests composed of tree species indigenous to the area with most of the principal characteristics and key elements of native ecosystems, such as complexity, structure and diversity"	Native species, natural regeneration, anthropogenic disturbance (recent)
Virigin forest	Barredo, 2021	Europe	Policymaking	"Its definition of virgin forests broadly overlaps with the concepts of primary forest, because considers forests that have not been influenced directly by human activities in their development."	Disturbance of ecological processes, anthropogenic disturbance (recent)
Forest undisturbed by man	Forest Europe, 2020	Europe	Policymaking	"Forests undisturbed by man are those in which the natural forest development cycle persists or was restored and show characteristics of natural tree species composition, natural age structure, deadwood component and natural regeneration and no visible signs of human activity"	Native species, natural regeneration, dead wood, anthropogenic disturbance (major / recent / visible, fine scale)
Intact Forest Landscape	Potatpov et al., 2017	Worldwide	Research	"We define an intact forest landscape (IFL) as a seamless mosaic of forests and associated natural treeless ecosystems that exhibit no remotely detected signs of human activity or habitat fragmentation and are large enough to maintain all native biological diversity, including viable populations of wide-ranging species. [...] Primary forests are part of IFLs, which also include nonforest intact ecosystems [...] 20% tree canopy cover threshold; naturally treeless ecosystems; >500km^2; Past disturbances that occured more than 30 to 70 years ago [...] nonindustrial timber harvesting by indigenous forest dwellers [...]."	Anthropogenic disturbance (major / recent), area size (large enough to self-maintain), canopy closure >20%, natural disturbance, indigenous and traditional use, intactness (unfragmented)

TYPE	SOURCES	LOCALISATION	OBJECTIVES OF DEFINITION	DEFINITIONS	CRITERIA
Secondary forest	Buchwald, 2005 (FAO)	Europe	Improve understanding of existing terminologies	"Forest stands of native species regenerated largely through natural processes after significant human and/or natural disturbance of the original forest vegetation and displaying a major difference in forest structure and/or canopy species composition with respect to primary forests on similar sites."	Anthropogenic disturbance (major), natural disturbance, native species, natural regeneration, difference in structure and canopy composition VS PF
Secondary forest	Secretariat of the Convention on Biological Diversity, 2001	Worldwide	Conservation	"Secondary forests have been directly disturbed by humans but have recovered, whether naturally or artificially. They do not necessary provide the same level of products and services as a primary forest would in the same location."	Difference in structure and canopy composition VS PF, anthropogenic disturbance (major)
Secondary forest	Chokkalingam & De Jong, 2001	Worldwide	Research	"Secondary forests are forests regenerating largely through natural processes after significant human and/or natural disturbance of the original forest vegetation at a single point in time or over an extended period, and displaying a major difference in forest structure and/or canopy species composition with respect to nearby primary forests on similar sites"	Anthropogenic disturbance (major), natural regeneration, difference in structure and canopy composition VS PF

ANNEX II - POTENTIAL TO OPERATIONALIZE CRITERIA IN GEOSPATIAL WORKFLOW

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
12	Anthropogenic disturbance (major)	PF, SF, OG, FUM, IFL	Data on harvest and clear-cuts (land-use change)	Temporal coverage may be too short; Harvest data may be incomplete; Temporal coverage may vary by province	Canada Landsat Derived Forest harvest disturbance 1985-2020 (Hermosilla et al., 2016)	Recent harvest and clear-cut events	Récolte et autres interventions sylvicoles (Ministère des Ressources naturelles et des forêts du Québec, 2023)	This is an example of governement data which tracks recent logging concessions and cutblocks. At the Federal level, NIR2024 (not available as of May 2024) should introduce the first harmonization of sub-federal harvest data.
11	Anthropogenic disturbance (recent)	PF, OG, VF, FUM, IFL	Data on harvest and clear-cuts (land-use change); Remote sensed data and federal/sub-federal data on harvest and human-caused wildfires	Harvest data may be incomplete; Historical length may vary by province	Canada Landsat Derived Forest harvest disturbance 1985-2020 (Hermosilla et al., 2016); Tree Cover Loss dataset 2000-2022(Hansen et al., 2013)	Recent harvest and clear-cut events; Landsat-derived Forest loss	Canadian National Fire Database 1980-2021	Federal harmonization of provincial and territorial forest fire data. Tracks if the fire originated from anthropogenic or natural sources.Temporal coverage for select provinces go back to the 1920s.
9	Natural regeneration	PF, SF, OG, VF, FUM	Exclude forests resulting from plantations and sylviculture. Could potentially operationalize an index of yearly rate of change combined with stand species similitude.	Currently no Canada-wide dataset on tree plantations, although there are some sub-federal level inventories data available. Some recent research is available on the topic.	IEQM5 (Ministère des Ressources naturelles et des forêts du Québec, 2023)	Tracks plantation type and year of plantation (provincial data, only tracks the south of the province)	Huang et al., 2023	AI-based method to map tree species in plantation forests using remote sensing.

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
7	Native species	PF, SF, VF, FUM	Remotely sensed forest canopy species: Using the Biodiversity Intactness Index to identify areas with high values for original community.	Remote sensing cannot account for understory species, native or not.	Canada Tree Species 2019 (Hermosilla et al., 2022)	Picea Abies (Norway Spruce) is a possible canopy value. Other invasive tree species are untracked (e.g. Pinus sylvestris, Ailanthus altissima)	Biodiversity Intactness Index (Gassert et al.,2022)	The Biodiversity Intactness Index (BII) estimates how the average abundance of native terrestrial species in a region compares with their abundances before pronounced human impacts.
4	Presence of dead wood	PF, OG, FUM	Current advances only touch on airborne-lidar imaging of standing dead trees or field based methods. A method coupling DBH, above-ground carbon and estimated stand age could be operationalizable in the future.	Not currently feasible at Canada-wide scale	None	None	Woodall et al., 2021; Neumann et al., 2023	Recent research showing the possibility of modelising dead wood distribution through thorough forest inventories
4	Natural disturbance	PF, SF, OG, IFL	Data on disturbance (insect defoliation, stand replacing fires)	Temporal coverage may be too short; May be incomplete. Currently no harmonized	Canada Landsat Derived Forest harvest disturbance 1985-	Recent stand replacing fire events	Hall et al., 2016	Geomatics Canada report on the remote sensing of insect defoliation.

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
				Canada-wide dataset on non stand-replacing disturbances	2020 (Hermosilla et al., 2016)			
4	Anthropogenic disturbance (visible, fine scale)	PF, FUM	None	Not currently feasible at Canada-wide scale	None	None	None	None
3	Disturbance of ecological processes	PF, VF	Anthropogenic pressure (human footprint or modelisation of ecosystem integrity) could serve as a proxy for the large-scale disturbance of ecological processes.	Approximative at best. Forest roads cover a large area of Canada's forests and they are badly represented global datasets.	The Canadian Human Footprint (Hirsh-Pearson et al., 2022)	Anthropogenic pressures modelised Canada-wide using twelve different human pressures (roads, mining, forest, agriculture)	Ecosystem Integrity Index (Hill et al., 2022)	The Ecosystem Integrity Index measures the ecosystem based on structure, composition and function (net primary productivity) measured against a natural baseline (the current potential). The Canadian Human footprint is likely more precise (using Canadian data) yet lacks certain parameters found here, such as net primary productivity.
2	Area size (large enough to self-maintain)	PF, IFL	Readily mappable using GIS tools	None	Forest Landscape Integrity Index (Grantham et al 2020; Potapov et al., 2017)	Through their analysis of IFLs, certain forest patches are excluded according to their size. Note that IFLs are not PFs	None	None

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
3	Anthropogenic disturbance (ever)	PF	Governmental data on historical cutblocks and harvest concessions. Modelisation of land-use land-cover change (i.e. deforestation for the purpose of agriculture, and subsequent aforestation)	Data gap in representing historical (pre 1985) harvest and clear-cuts. Some provincial data on harvest go back to the 1910s, but most likely incomplete.	Récoltes et autres interventions sylvicoles anciens (avant 1976) (Ministères des Ressources Naturelles et des Forêts du Québec, 2022)	Quebec-scale data on logging and harvest, going back to 1919. Most likely incomplete. Few provinces and territories have consistent historical records harvest in the early 20th century.	Land-use Harmonization 2 (LUH2) (Hurtt et al., 2020)	Low-resolution dataset which estimates worldwide historical land-use changes from 850-2100. This could track post-colonisation deforestation and agricultural practices in Canada, although the resolution is quite coarse.
3	Presence of old-growth (late-successionnal) tree species	OG	Remotely sensed forest canopy species or inventory data; forest inventories may have age class data, which could help operationalizing a species-dependant age class threshold for Old-Growth.	Remote sensing cannot account for understory species.	Canada Tree Species 2019 (Hermosilla et al., 2022)	Caracterisation of dominant canopy species.	IEQM5	This is an example of a provincial stand-level inventory, since there exists no field-based federal inventory. Stand-level inventories such as this one may have age class data.

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
3	Indigenous and traditional use	PF, IFL	Not feasible at the scale of Canada. Initial operationalization could be provided using spatial data on land management.	Requires fine-scale data gathering with Canada's Indigenous people. Requires data on historical traditional practices for e.g harvest, religious and cultural activities. Land that is considered as traditional might have been subject to large-scale colonizer harvest practices.	Map of Forest Management in Canada (National Forest Inventory)	Classification of Canadian forest management areas. Includes treaty/settlement areas and Indian reserves.	None	None
3	Canopy closure	PF, OG, IFL	Remote sensing allows for an analysis of the canopy cover/crown closure percentage.	None	Canadian Satellite-Based Forest Inventoy (SBFI) (Wulder et al., 2024)	Column for canopy closure percentage.	None	None
3	Difference in structure and canopy composition VS PF	SF	Mapping secondary forests falls outside of the scope of this study.	None	None	None	None	None

FREQUENCY	CRITERIA	SUBJECT	OPERATIONALIZATION	LIMITATIONS	RELEVANT DATASET	NOTES	OTHER RELEVANT METHODS OR SECOND DATASET	NOTES (BIS)
2	Intactness (unfragmented)	PF, IFL	Following Potapov et al. (2017) methods on mapping intact forest landscapes: Adding a 1 km buffer zone around roads, pipelines, powerlines and navigable rivers; Minimal area size of 50,000 ha, minimum width of 10 km, minimal corridor with of 2 km	Forest roads should be added to the fragmentation operationalization, although they are rarely precisely mapped in global datasets.	Potapov et al., 2017	None	Subfederal datasets on forest roads data.	Forest roads cover a large area of Canada's forests and fragment it. They are usually not precisely mapped in global datasets. In the absence of a federal geospatial dataset on forest roads, one parse through publicly available subfederal datasets.

ANNEX III - RELEVANT DATASETS

For complete dataset information, see attachment.

INCLUDED IN OPERATIONALIZATION?	NAME	LOCATION	CREATOR	TYPE	YEAR	TEMPORAL COVERAGE	DESCRIPTION	RESOLUTION /SCALE	PUBLICATION
No	EPFD 2.0 - European primary forest database	Europe	Sabatini et al., 2021	Polygons and points	2021	NA	Primary forest data harmonization. Mostly field-based (i.e. directly contacting local authors, orgs and groups attending to the relevent land). Validation using Landsat data (1985-2020) in order to account for recent harvest.	NA	Sabatini et al., 2021
No	Map of Forest Management in Canada	Canada	National Forest Inventory (NFI)	Raster and Polygons	2019	2017-2020	Classification of Canadian forest management areas. This includes protected areas, Treaty/Settlement areas, Indian Reserves, provincial and territorial reserves, private lands, Crown forest tenure areas and areas with no Crown timber dispositions.	NA	NA
Yes	Canada Landsat Derived Forest harvest disturbance	Canada	Hermosilla et al., 2016; National Forest Inventory (NFI)	Raster	2016	1985-2020	Times series of Landsat data, "derived in a fully automated manner", that classifies forests according to their most recent disturbance event (harvest or fire)	30m	Hermosilla et al., 2016
Yes	SBFI - Satellite-Based Forest Inventory	Canada	Wulder et al., 2024; National Forest Inventory (NFI)	Polygons	2024	1984-2019	Times series of Landsat forest data. Automatic derivation of land cover (forest types), time since disturbance, forest age [0-150] (Maltman et al., 2023)	30m	Wulder et al., 2024

INCLUDED IN OPERATIONALIZATION?	NAME	LOCATION	CREATOR	TYPE	YEAR	TEMPORAL COVERAGE	DESCRIPTION	RESOLUTION /SCALE	PUBLICATION
No	Canada Tree Species 2019	Canada	Hermosilla et al., 2020; Naitonal Forest Inventory (NFI)	Raster	2019	NA	Tree species presence and distribution across Canada, infered through remote sensing. 37 different tree species. Includes 'distance to second' class, which is a confidence index that tracks the probability of a second tree species being the most popular within the cell.	30m	Hermosilla et al., 2020
No	FAO Forest 2019	Canada	Wulder et al., 2020	Raster	2019	NA	Forest areas consistent with FAO definitions. Based on land use, i.e. harvested/burnt/disturbed forests are still considered as forests. FAO definition excludes forest patches where tree height is lower than 5 meters and canopy lower than 10%.	30m	Wulder et al., 2020
No	Forest Landscape Integrity Index	Worldwide	Grantham et al., 2020	Raster	2019	NA	Forest landscape integrity raster, based on the harmonization of forest extent, pressure from infrastructure and harvest, forest connectivity.	300m	Grantham et al., 2020
No	LUH2 - Land-Use Harmonization v2	Worldwide	Hurtt et al., 2020	Raster	2018	850-2100	Global land use change. Uses historical data from the History of the Global Environment database (HYDE)	0.25 degrees (900 arc-seconds/~30, 000m)	Hurt et al., 2020
No	NIR 2024 - National Inventory Report on greenhouse gas sources and sinks in Canada	Canada	ECCC	?	ETA 2024	1890-1989	Contains harmonization of federal, provincial and territorial data on historical harvest, going back to 1890. ETA 2024	NA	NA

INCLUDED IN OPERATIONALIZATION?	NAME	LOCATION	CREATOR	TYPE	YEAR	TEMPORAL COVERAGE	DESCRIPTION	RESOLUTION /SCALE	PUBLICATION
No	Primary Humid Tropical Forests	DRC, Brazil and Indonesia	Turubanova et al., 2018; GLAD Team, University of Maryland	Raster	2018	NA	Full mapping of primary forests focused on Brazil, DRC and Indonesia. Their definition of PF is mostly age-based, although they also use a definition and methods for the mapping of intact forest landscapes (IFL)	30m	Turubanova et al., 2018
No	Landsat-derived forest age for Canada's forested ecosystems	Canada	Maltman et al., 2023	Raster	2023	1869-2019	Estimating and mapping Canada's forest age across ecosystems. Three datasets: 1985-2019 detects time since disturbance; 1965-1985 estimates the time since regrowth based off 1985 data, up to 20 years. 1869-2019 models forest age using canopy heigth.	30m	Maltman et al., 2023
No	IFL - Intact Forest Landscape dataset	Worldwide	Potapov et al., 2017;IFL Mapping Team; GLAD Lab	Raster	2021	2000-2020	Tracks Intact Forest Landscape loss for the years 2000, 2013, 2016 and 2020.	1:1,000,000	Potatpov et al., 2017
No	Global Register of Introduced and Invasive Species - Canada	Canada	Invasive Species Specialist Group	Column data	2022	NA	Validated list of invasive species in Canada - both plant and non-plant species	NA	NA
Yes	The Canadian Human Footprint	Canada	Hirsh-Pearson et al., 2021	Raster	2021	2021	Anthropogenic pressures modelised using twelve different human pressures (roads, mining, forest, agriculture)	300m	Hirsh-Pearson et al., 2021

INCLUDED IN OPERATIONALIZATION?	NAME	LOCATION	CREATOR	TYPE	YEAR	TEMPORAL COVERAGE	DESCRIPTION	RESOLUTION /SCALE	PUBLICATION
Yes	Canadian National Fire Database	Canada	John Little (Natural Resources Canada, Canadian Forest Service)	Polygons	2024	1980-2020	Harmonization from Canadian fire management agencies -includes data from Parks Canada, provinces and territories. Data for some provinces goes back to the 1920s. Data is labelled by creator as being incomplete.	NA	NA
Yes	Biodiversity Intactness Index	Worldwide	Impact Observatory, Vizzuality	Raster	2022	2017-2020	Biodiversity (plants, fungi, animals) change according to human pressures (land-use change). Compares selected years to a modelised baseline of intact biodiversity. Based on the PREDICTS database of global biodiversity.	100m	Gassert et al., 2022
Yes	Tree Cover Loss Dataset (Global forest loss)	Worldwide	GLAD Team, University of Maryland; Global Forest Watch	Raster	2013	2000-2022	Annually updated global-scale forest loss data. Includes forest extent layer with values for canopy cover.	30m	Hansen et al., 2013
No	Ecosystem Integrity Index	Worldwide	Hill et al., 2022; Single.Earth	Raster	2022	NA	The Ecosystem Integrity Index measures the ecosystem based on structure, composition and function (net primary productivity) measured against a natural baseline (the current potential).	1000m	Hill et al., 2022

www.habitat-nature.com

5818 Blvd Saint-Laurent, Montréal, H2T 1T3, QC

info@habitat-nature.com | (438) 825-4445