Comparing global and regional maps of intactness in the boreal region of North America: implications for conservation planning in one of the world’s remaining wilderness areas

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# Abstract

Though North America’s boreal forest contains some of the largest remaining intact ecosystems in the world, human activities are systematically reducing its extent. Consequently, forest intactness and human impact maps are increasingly used for monitoring and conservation planning in the boreal region. We compare ten forest intactness and human impact maps to provide a multi-model assessment of intactness in the boreal region. All maps are global in extent except for Global Forest Watch Canada’s 2000 and 2013 Intact Forest Landscapes (IFL) maps, although some global maps are restricted to areas that were at least 20% treed. As a function of each maps spatial coverage in North America, the area identified as intact ranged from 56% to 79% in Canada and from 32% to 84% in Alaska. Comparisons of spatial similarity between the maps revealed some broad patterns of agreement with regional variations due to differences in resolution, input data, mapping methods, and width of anthropogenic zones of influence. A regional assessment of the accuracy of the 4 most recent maps using finer-resolution datasets from Alberta, BC and Yukon revealed that seismic lines and mining sites are often misclassified as intact while recent cutblocks are generally accounted for. In frontier ecosystems such as Canada’s boreal region, where detailed regional mapping does not exist, we recommend high-resolution maps such as Global Forest Watch Canada’s 2013 IFL map but recognize its limitations and emphasize the need to match map characteristics to conservation objectives. Moreover, in landscapes that are undergoing rapid change due to development, maps that are regularly updated using standard procedures are highly desirable.

# Introduction

North America’s boreal forest contains some of the largest remaining intact ecosystems in the world (Potapov et al. 2017, Watson et al. 2018). However, the rapid expansion of industrial activities such as forestry, mining, and oil and gas exploration into increasingly accessible landscapes is systematically reducing its extent (Bradshaw et al. 2009, CEC 2010, Schindler and Lee 2010, Brandt et al. 2013, Venier et al. 2014). Large intact areas support biodiversity, ecological and evolutionary processes including wildlife migrations and natural disturbances, and ecosystem services such as carbon capture and sequestration (Mittermeier et al. 2003, Leroux et al. 2010, Watson et al. 2016). They also play an important role in climate change mitigation (Price et al. 2013, Melillo et al. 2016) and can serve as ecological baselines to guide sustainable land management practices (Arcese and Sinclair 2016). Despite their importance and recent calls for the expansion of protected areas in wilderness or intact regions (Betts et al. 2017, Dinerstein et al. 2017, Tilman et al. 2017), the global erosion of wilderness areas has exceeded their rate of protection (Watson et al. 2016). To identify and conserve additional wilderness and intact areas, reliable and up-to-date spatial information is required. This has led to the production of several global and regional datasets that attempt to map anthropogenic disturbances or their complement, areas with little or no evidence of human activities (McCloskey and Spalding 1989, Bryant 1997, Sanderson et al. 2002, Potapov et al. 2008b, Hansen et al. 2013). The maps vary in methodology, spatial and temporal characteristics, and most importantly, the area estimated to be intact in the boreal region. Consequently, a comparison of map products would assist conservation planners and researchers with the selection of the most appropriate product(s) to use for their purposes.

The boreal region covers 6.3 million km2, of which 88% is in Canada and 12% is in Alaska (Brandt et al. 2013). In Canada, 11.4% of the boreal region is currently under some form of protection (CPCAD 2019). Both globally and in Canada, there is increasing recognition of the need to expand protected areas while opportunities remain. In response, the United Nations Convention on Biological Diversity developed a set of goals (“Aichi Targets”) for protecting biodiversity which includes a target of 17% of terrestrial areas conserved by 2020 (Butchart et al. 2016), with a proposed increase to 30% by 2030 (Dinerstein et al. 2019). At the regional level, the Governments of Ontario and Quebec have committed to setting aside 50% of the boreal region of each province in various levels of protection in anticipation of future resource development (Government of Quebec (Minister of Natural Resources and Wildlife) 2009, Hansen et al. 2010, OMNR 2013). In addition, several major forest companies and environmental organizations have signed the Canadian Boreal Forest Agreement (CBFA 2010), which aims, amongst several key goals, to complete a network of protected areas that is representative of ecosystem diversity across the boreal region. The Agreement also seeks to secure ecological benchmarks (Arcese and Sinclair 2016), defined as areas of intact forest large enough to sustain biodiversity and support large-scale ecosystem processes such as fire with minimal external inputs (Lee et al. 2006, Potapov et al. 2008b, Cyr et al. 2009, Potapov et al. 2017). Consequently, intact areas play an important role in protected area design and as control areas against which the impacts of human activities on biodiversity can be compared within an adaptive management framework (Lindenmayer et al. 2006, Watson et al. 2009).

In the boreal region where forests dominate the landscape, wilderness or intact areas have much in common with the concept of intact forest landscapes (Potapov et al. 2008a). Intact areas become non-intact through the accumulation of human impacts such as road construction, logging, mining, and urban development. Specific definitions for intactness differ by map product, but in general, the products consider intactness to be a structural descriptor of landscapes that reflects the absence of anthropogenic disturbances as measured from thematic (e.g., roads) and remote sensing data. Maps that measure intactness can be used along with other information to evaluate the sustainability of forest management (Heilman et al. 2002, Wulder et al. 2008), monitor trends in biodiversity and other forest resources (Coops et al. 2009, Fraser et al. 2009), assess the effectiveness of conservation strategies (Haines et al. 2008, Leroux and Kerr 2013), and inform conservation planning and policy decisions (Myers et al. 2000, Wiens et al. 2009, Leroux et al. 2010). Moreover, intact forest landscapes are increasingly considered a policy instrument in forest conservation and management. For example, they have been integrated into the certification standards of the Forest Stewardship Council (FSC 2015) with implications for forest management policies (Rotherham 2016). Their use in current form, however, has been questioned, especially in the context of the boreal region where a more sophisticated approach has been suggested, one that considers intactness as a gradient rather than a binary condition and where the minimum patch size is not standardized but guided by regional ecological conditions and processes (Bernier et al. 2017, Venier et al. 2018).

Several global and regional initiatives have attempted to map the overall condition of the world’s ecosystems in the past 30 years. The initiatives can be divided into two broad groups based on their objective: intactness mapping and cumulative human disturbance (pressure) mapping. The intactness mapping approach attempts to map remaining areas with little or no human influence by removing anthropogenic disturbances that are detectable using satellite imagery and other input data, and sometimes applying a zone of influence buffer. Resulting areas are considered to be free from significant human influence. In contrast, the cumulative disturbance mapping approach combines multiple disturbance layers into an overall map showing areas of low to high disturbances. Areas with the least amount of disturbance can then be reclassified to identify relatively intact areas. Among the intactness mapping approaches, the World Wilderness Areas map was one of the first global initiatives that attempted to map areas with little or no human influence (McCloskey and Spalding 1989). To qualify, areas had to be ≥ 4,000 km2 after eliminating all areas within 6 km of human infrastructures e.g., roads and settlements. Subsequently, the Frontier Forests initiative also attempted to map the world’s remaining large intact natural forests (Bryant 1997). No explicit minimum size for inclusion was specified and similar to wilderness areas, human disturbances due to traditional activities were considered acceptable. The concept, however, has been questioned for its utility for identifying high priority conservation areas because of the methods and criteria used to define intact forests (Innes and Er 2002). More recently, Potapov et al. (2008b) built upon the concept of the Frontier Forest to define an Intact Forest Landscape (IFL) as “a seamless mosaic of forest and naturally treeless ecosystems within the zone of current forest extent, which exhibit no remotely detected signs of human activity or habitat fragmentation and is large enough to maintain all native biological diversity, including viable populations of wide-ranging species”. IFLs are delineated using specific criteria related to minimum size, patch width, and corridor width. The approach has been applied at global and regional scales, although in Canada it diverges from the global definition with respect to some of the criteria, for example the treatment of wildfires (see Discussion).

Several cumulative human disturbance datasets have also been developed in the past two decades. The best known is the Human Footprint (HFP), which provides a standardized measure of cumulative human pressures on the environment based on the extent of built environments, crop land, pasture land, human population density, night-time lights, railways, roads and navigable waterways (Sanderson et al. 2002). The dataset has recently been updated to the year 2009 while keeping the methods consistent with the orginal version (Venter et al. 2016a). Both the original and more recent versions can be used to identify the least disturbed areas (“Last of the Wild”) by reclassifying all areas with little or no disturbances. Another well known dataset is the Anthropogenic Biomes map (Ellis and Ramankutty 2008) which classifies the terrestrial biosphere into 19 categories based on human interactions with ecosystems, including agriculture, urbanization, forestry and other land uses. The two wildland categories (wild forest, sparse trees and barren) represent areas of least disturbance. Two more recent datasets, the global Human Modification map (Kennedy et al. 2019) and the Low Impact Areas map (Jacobson et al. 2019) also provide a cumulative measure of human modification of terrestrial lands across the globe at a 1-km2 resolution for the year 2015. Both approaches are similar to the HFP approach but differ in the number and recentness of anthropogenic stressor datasets, and the methods used to calculate human influence.

The availability of an increasing number of intactness and disturbance maps may lead to confusion about the suitability of the various products for conservation planning. To make a choice, it would help to not only understand the differences in characteristics and assumptions of each map, but also how well their predictions agree with each other and against independent and higher-resolution regional maps. Consequently, we compare map characteristics and intactness estimates, and quantify inter-map agreement. We then illustrate the strengths and limitations of the maps at accurately identifying specific anthropogenic disturbances common in the boreal region: oil and gas exploration, logging, roads, and mining. Our goal is to inform conservation planning in one of the world’s remaining wilderness areas.

# Methods

## Study area and map characteristics

Our study area comprises the spatial extent of the boreal and boreal alpine regions (i.e., the boreal region) of Canada (Brandt 2009) (Figure 1). We also provide provide distribution maps and summary statistics for the Alaska boreal region (Table 2; Supp info). We selected nine recent national and global maps that are freely available and that, at a minimum, covered a large portion of the study region. All maps are global in extent except for the three developed by Global Forest Watch Canada for the Canadian boreal and temperate forests. Four of the maps have been produced for 2-3 time periods (Table 1). The maps can be broadly categorized into those that attempt to map intactness directly and those that map cumulative human disturbances, from which intact areas can be deduced. Among the former group, three of the maps used similar methods to measure intactness as the absence of conspicuous anthropogenic disturbances: Frontier Forests (FF1996) map for 1996 produced by the World Resources Institute (Bryant 1997); Global Forest Watch’s (GFW) global intact forest landscapes (IFL) maps for the years 2000, 2013 and 2016 (GIFL2000, GIFL2013 and GIFL2016) (Potapov et al. 2008b, 2017); and GFW Canada’s (GFWC) IFL maps for the years 2000 and 2013 (CIFL2000 and CIFL2013) (Lee et al. 2010, Smith and Cheng 2016). Five of the maps were developed by mapping cumulative human pressures on terrestrial ecosystems: Very Low Impact Areas for the year 2015 (VLIA2015) (Jacobson et al. 2019), Global Human Modification for the year 2015 (GHM2015) (Kennedy et al. 2019), Human Footprint maps for the years 1993 and 2009 (HF1993 and HF2009) (Venter et al. 2016a, 2016b), Anthropogenic Biomes for the year 2000 (AB2000) (Ellis and Ramankutty 2008, Ellis et al. 2010), and Canada’s Human Access map for 2010 (HA2010) (Lee and Cheng 2014).

We compared each map based on general characteristics including geographic extent, format, resolution, measurement scale, and source of input data. We also compared the methods used to develop the maps, including methods used to delineate or stratify the maps, minimum size of an intact area, disturbance types considered, and whether areas surrounding disturbances were excluded.

## Intactness estimates and agreement

The maps reviewed varied in geographic coverage, mapped values, scale, coordinate system, and GIS file format. To make comparisons of intactness estimates across maps at national ~~and regional~~ scales, we converted all maps to an Albers Equal Area projection, clipped to the boreal region of Canada and Alaska (Supp Info), and vectorized the raster datasets. We then reclassified the maps, where necessary, to binary “intactness” maps, with 1 indicating little or no human impact and 0 identifying non-intact areas. For the human footprint maps (HF1993 and HF2009), the global human modification map (GHM2015) and low impact areas map (VLIA2015), all areas with little or no human influence (pixel values=0) were assigned a value of 1 while remaining areas were assigned a value of 0. Similarly, for the HA2010 and BEAD2010maps we assigned a value of 1 to all pixels that were not identified as disturbed areas. For the frontier forest map (FF), all frontier forest polygons were assigned a value of 1, irrespective of their threat level. For the AB2000 map, we assigned a value of 1 to the wildland categories i.e., wild forest, sparse trees and barren. Following map reclassifications, we calculated, for each map, the geographical coverage of the mapped product within the boreal region as well as the total area identified as intact.

Prior to evaluating the spatial agreement of datasets, we rasterized or resampled all maps to a 250-m resolution. No information was lost when resampling original raster maps to a smaller cell size (e.g., HFP2009). We estimated the area of spatial agreement and disagreement between the 250-m intactness maps using the raster package (Hijmans 2016) in R 4.0.0 (Team n.d.). For the CIFL, GIFL and HFP maps, we used the most recent maps for the comparisons. We restricted the spatial extent of the analysis to the intersection of the GIFL, CIFL, and BEAD2010 datasets. For each comparison (i.e., each map pair), we report of the amount of spatial overlap in common between the two maps as well as the amount of intact area that is uniquely identified by each map.

## Regional assessments

We conducted three case studies to assess the ability of intactness maps to account for specific disturbance types common in the boreal region and to illustrate the benefits of using higher resolution regional data sources, when available, to create a more complete assessment of current landscape conditions (Figure 2, Table 5). The case studies focused on oil and gas exploration in Alberta, forest harvesting in Quebec, and mining in the Yukon. Other anthropogenic disturbances were also considered. For each intactness map in each study area, we calculated the total area (or length) that was misclassified as being intact. No buffer was applied to the linear and polygonal disturbances prior to the analysis and, consequently, estimates are considered to be conservative.

The first two cases studies come from Alberta and Quebec and used the same anthropogenic disturbance dataset to evaluate the intactness maps. In both cases, the specific study areas were defined by the boundary of a boreal caribou range (Figure 2a and 2b): Caribou Mountains in Alberta and Manouane in Quebec. In the first case study from northern Alberta, oil and gas exploration has expanded at a rapid pace in recent decades, leading to a proliferation of seismic lines, pipelines, roads and well sites across the landscape (Lee and Boutin 2006). Forest cutblocks are also a prominent feature on the landscape. In the second case study from central Quebec, forestry has been expanding rapidly from the southern edges of the study area, leading to an increasing number of cutblocks and associated roads. Other anthropogenic disturbances in the area including, mining and hydroelectric development.

To identify the various linear and polygonal disturbance types, we used the high-resolution boreal ecosystem anthropogenic disturbance (BEAD) dataset which was created specifically to identify disturbances in and around boreal caribou ranges (Pasher et al. 2013). The BEAD consists of unbuffered linear and polygonal disturbances and was initially produced in 2010 and covers 4.4 million km2 of the boreal including all 51 caribou ranges. It was updated in 2015 but restricted to the caribou ranges. The BEAD maps consist of vector polygons which map the distribution of linear and polygonal anthropogenic disturbances related to energy extraction, forestry, agricultural, and human settlements. They were produced 30-m resolution satellite imagery in 2010 and both 30- and 15-m resoluton Landsat 8 data in 2015. We used 2010 BEAD dataset (30-m) to evaluate HF2009, HA2010, CIFL2013 and GIFL2013 datasets and the 2015 BEAD datasets (15- and 30-m) to evaluate the CIFL2013, GIFL2013, GIFL2016, GHM2015 and VLIA2015 datasets. We did not evaluate the other intactness maps due to the large temporal disconnect with the earliest BEAD map produced. Prior to the analysis, we converted the HFP2009 map to a vector map. We then intersected each intactness map with the matching BEAD map and calculated the area and proportional area of individual polygonal disturbances and the length and proportional length of individual linear disturbances that were located within areas identified as intact.

The third case study is from central Yukon Territory near the Alaska border (Figure 2c) where placer mining, the technique of recovering gold from gravel along streams and rivers, is a relatively common land use activity with claims extending across more than 2 200 km2 of the Territory (Ref). The study area consists of the Indian River watershed, an area comprising numerous streams and rivers that are actively being mined for gold. We used two recently produced datasets to identify linear and polygon disturbances associated with placer mining. The earlier dataset was developed in 2010 for an area larger than the Indian River watershed[[1]](#footnote-1) while the later dataset was an update for a smaller area i.e., the Indian River watershed[[2]](#footnote-2). As with the other two case studies, we intersected the vectorized versions of the intactness maps with the two linear and polygonal disturbance maps to identify areas that were erroneously mapped as being intact. As with the Alberta case study we matched the year of the disturbance data to the closest year of the intactness map i.e., we used to the 2017 disturbance datasets to evaluate GIFL206, VLIA2015 and GHM2016 and the 2010 datasets to evaluate HA2010, CIFL2013, HFP2009, and AB2000. Two intactness datasets, FF1996 and BEAD2010, were not used since they did not occur in the study area.

# Results

## Map characteristics

Six of the nine datasets that we evaluated have global or near-global extents, the exceptions being the national-scale CIFL and HA2010 maps, the BEAD2010 map which covers a large portion of the boreal region, and the BEAD2015 which covers 51 caribou ranges within the boreal (Table 1). Map resolutions varied from relatively fine (CIFL, GIFL and HA2010 effective resolution ≈ 0.25 km2) to the relatively coarse AB2000 (resolution ≈ 5 km2) and FF1996 (resolution ≈ 16 km2) maps. The nine datasets were generated from combinations of remote-sensing data and thematic maps representing land use, land cover, human infrastructure, and other spatial and non-spatial information. Thematic maps were used in all cases to represent anthropogenic features such as roads, settlements, and population density. With the exception of the FF1996 map, satellite imagery was used to map forested areas and identify other areas with detectable human activity. In some cases, the use of the same input data resulted in different estimates due to how disturbances were treated. For example, in contrast to the CIFL maps, the GIFL maps considered all stand-replacing fires near settlements and infrastructure as being non-intact (Lee 2008). Data production methods also differed with respect to study area delineation and minimum mapping unit. For example, minimum patch size for the HFP and GIFL maps was 50,000 ha while for the CIFL maps it was 5,000 ha. In contrast, the HA2010 map did not have a minimum patch size. In addition, methods differed in the process by which areas of human impacts were detected and delineated. Some of the maps distinguished between types of human disturbances and assigned different zones of influence to different disturbance types using buffers e.g., HFP maps. This strongly influenced the distribution and abundance of areas identified as intact forests. Three maps used buffer zones to either eliminate non-intact areas or to rank areas by the degree to which they were influenced by roads, powerlines and navigable waterways. For example, the HA2010, CIFL and GIFL maps systematically eliminated areas within 0.5-1 km of all human disturbances as measured from pre-existing thematic maps or as visually identified on Landsat Thematic Mapper imagery. In contrast, the AB2000 map used cluster analysis to identify and map 19 zones based on factors such as human population density, land use and land cover, including the wild woodlands and wild treeless and barren lands that were use in the analysis. Need to add something about GHM2015 and VLIA2015…

## Intactness estimates and agreement

All maps except for the BEAD2010 and GIFL maps covered at least 98% of the boreal region of Canada as defined by Brandt (Brandt 2009) (Table 2, Figure S1). The CIFL maps were restricted to the Canadian boreal region, covering 98% of the region while the three GIFL maps covered 86% of the boreal region of Canada. The BEAD2010 dataset was the least extensive, covering 79% of the boreal region. The total area identified as intact within the extent of each map, ranged from 36% for the GHM2015 map to 95% for the BEAD2010 map. On the high end, AB2000 and HA2010 identified 86% and 84% of the boreal region as being intact, respectively. Conversely, the area identified as intact by the GIFL map ranged from 59% in 2000 to 55% in 2016. The FF1996 map was also relatively low, with only 60% of the boreal identified as intact. Other datasets were somewhere in between ranging between 69% (HFP2009) and 76% (VLIA2015). The CIFL2016 map identified 3.6% less intact forest than the 2013 map while the HFP2009 identified 2.2% less intact area than the 1993 version of the map. In Alaska, the area identified as intact also varied widely as in Canada (Table S2): from 23% for the GHM2015 map to 91% for the AB2000 map. The GIFL2016 map identified 6.0% less intact area than the GIFL2000 map while the difference between the HFP2009 and HFP1993 maps was only 0.2%.

Spatial agreement, as measured by the areal overlap between intactness maps, varied widely between comparisons, ranging from a low of 39% between GHM2015 and both VLIA2015 and BEAD2010 to a high of 86% between BEAD2010 and AB2000 (Table 3, Figure 3). The amount of overlap is partly related to the area identified as intact by each map. For example, BEAD2010, which identified the greatest amount of intact landscapes among all datasets, had at least 69% agreement in all comparisons except with GHM2015 and GIFL2013 (56%). The AB2000, HA2010 and FF1996 datasets also identied relatively large amounts of intact area and, in all comparisons except with GHM2015, had at least 56%, 65% and 65% agreement, respectively. Conversely, the dataset which identied the least amount of intact habitat, GHM2015, never exceed 48% overlap with the other datasets. The spatial overlap between the two GFW products, CIFL2013 and GIFL2013, was 76%, reflecting differences in how forest fires were treated. Likewise, the agreement between HA2010 and CIFL2013, both created by GFWC, was also relatively high (82%), with the additional buffers in the CIFL2013 map accounting for most of the differences. The area uniquely identified as intact also varied greatly between map pairs, ranging from a low of 0.1% for CIFL2013 and GIFL2013 in comparison to BEAD2010 to a high of 60% for BEAD2010 in comparison to GHM2015.

## Regional assessments

*Seismic lines in Alberta*. Most of the seismic cutlines occurred in the southern half of the study area and were established prior to 2007 (Figure 2). Eights intactness datasets were evaluated for this case study – those that were developed within two years of one of the ABMI footprint dataset (Table 4). This excluded, in particular, the FF1996 and AB2000 maps from the analysis. The area identified as intact in the study area ranged from 49% for the GIFL2016 map to 91% for the GHM2015 dataset. Most intactness maps were relatively poor at accounting for seismic lines, probably because they are difficult to detect without high resolution aerial photos or satellite imagery (Table 1). The GHM2015 map, in particular, misclassified almost all seismic cutlines (97%). The HFP2009, BEAD2010 and VLIA2015 also performed poorly, misclassifying 70%, 69% and 60% of cutlines, respectively. The HF2009 failed to identify the majority of seismic lines with the exception of a few in the northwest that were removed by the placement of a buffer around the navigable Peace river. The results for the BEAD2010 dataset are likely biased due to slight differences due to the use of different underlying coordinate systems which resulted in slight differences in the positioning of seismic cutlines (see zoomable map in Supp info). The GIFL2013 and GIFL2016 performed best, misclassifying only 4% and 7% of cutlines, respectively. The CIFL2013 and HA2010 were somewhere in between, misclassifying 19% and 39% of seismic cutlines. The difference is between the GIFL and CIFL2013 maps is due in part to a large section of the study area being identified as non-intact in the GIFL2013 map in comparison to the CIFL2013 map, possibly due to differences in the treatment of wildfires (see Discussion).

*Forest harvesting in British Columbia*. All datasets were used in the British Columbia case study, although the BEAD2010 map only covered 69% of the study region, albeit the entire area disturbed by cutblocks. The datasets varied widely in the area identified as intact and the proportion of cutblocks misclassified. The GHM2015 stood out with only 4% of the area identified as intact and, consequently, less than 1% of cutblocks misclassified. The VLIA2015 map also misclassified a majority of recent cutblocks (61%). On the other end of the scale, the BEAD2010 and AB2000 maps identified 97% and 96% of the study area as intact, respectively. However, there were large differences in the area misclassified, with the AB2000 misclassifying 88% of the cutblocks compared to 25% for the BEAD2010. The three GIFL maps were unique among the datasets by not misclassifying any of the cutblocks. The two GIFL maps were also very good, misclassifying only 5% and <1% of cutblocks in 2000 and 2013, respectively. The HA2010 map misclassified more cutblocks than the related CIFL2013, reflecting the use of a minimum patch size in the mapping process of the latter dataset. Among the two HFP datasets, the HFP2009 misclassified 27% of the cutblocks versus 19% in 1993, reflecting the increasing inability of this dataset to detect recent cutblocks in the region.

*Placer mining in the Yukon*. Two datasets, FF1996 and BEAD2010, did not cover the Yukon study area and were thus excluded from the analysis. Among the 7 remaining datasets, the GIFL2016 and GHM2015 misidentified the least amount of mining disturbances (0.0% and 0.1%, respectively) and linear disturbances (1.9% and 6.5%, respectively) among the datasets (Table 6, Supp info). However, both also identified the least amount of intact area in the study region. Conservely, the VLIA2015 and HFP2009 datasets both misidentified a very large proportion of both mining disturbances (99% and 91%, respectively) and linear disturbances (98% and 85%, respectively). In the case of VLIA2015, this was clearly due to this dataset identifying 97% of the study area as being intact. AB2000 also misidentified a large proportion of linear (75%) and mining (55%) disturbances. The other two datasets, CIFL2013 and HA2010 misidentified a moderate amount of both mining (12% and 22%, respectively) and linear (21% and 38%, respectively) disturbances, the difference likely due to the minimum patch size requirement used the former dataset.

# Discussion

There is increasing interest in the use of intactness maps for conservation planning, especially in regions with prior to land conversion and natural resource development (Brandt et al. 2013, Venier et al. 2014). The North American boreal region remains relatively intact in comparison to much of the globe but is under increasing pressure from forestry, oil and gas operations, mining and hydroelectricity development (Bradshaw et al. 2009, Leroux and Kerr 2013, Venier et al. 2014). Efforts are underway to increase the level of protection in the boreal, and these efforts are focusing on areas that are presently intact, or little-influenced by humans. Intactness is an emerging criterion in conservation planning (Haines et al. 2008, Lee et al. 2010, Watson et al. 2016, Dinerstein et al. 2017), but there is no universally accepted means to measure it over large extents. This has resulted in a number of new global and regional datasets that purport to identify intact areas or their opposite cumulative human pressures. We compared nine global and regional maps depicting forest intactness or human impacts on ecosystems to explore the nature, extent, and spatial agreement between maps. Overall, the proportion of the boreal region identified as intact ranged from 36% (GHM2015) to 84% (HA2010) in Canada and 23% (GHM2015) to 91% (AB2000) in Alaska. The BEAD2010 dataset identified a larger proportion of intact areas (95%) but within a subregion of the boreal. The relatively low percentage identified by the GIFL maps is due in part to its restricted coverage within the boreal region compared to the other maps, and its treatment of all wildfires occurring in proximity to infrastructure as being considered non-intact (Lee 2008).

Among map characteristics, important factors are spatial resolution and year of production or image capture of the underlying spatial data (i.e., thematic maps and satellite imagery). The FF1996 and AB2000 maps had the coarsest resolution. This likely resulted in many finer-scale anthropogenic changes and disturbances not being detected in those maps in comparison to the BEAD2010, HA2010, CIFL and GIFL maps, which used finer-resolution Landsat imagery. ~~Some global-scale maps relied on older thematic maps such as the Digital Chart of the World to represent infrastructure~~. Increasingly, maps are using freely available satellite imagery or satellite-based land cover maps as inputs (e.g., Landsat) (White et al. 2017). The age of the imagery could have important implications for the suitability of these maps in conservation planning, especially in areas that are rapidly changing, including the boreal plains of western Canada, and southern parts of the boreal shield in Ontario and Quebec (Government of Quebec (Minister of Natural Resources and Wildlife) 2009, OMNR 2013).

Methodological differences among maps were mostly related to study area delineation, minimum polygon size, and map age. For example, some of the discrepancy between the FF1996 and CIFL maps is due to the delineation of the FF1996 forest zone, which excluded northern, less densely forested portions of the Canadian boreal. Similarly, many disagreements occurred where older maps did not reflect areas of recent rapid development along southern boundaries. Some of these characteristics may explain why the CIFL maps are more consistent with the known history of development over the past 20 years than some of the other maps. The GIFL maps used a satellite-based global tree cover map to define their study area, resulting in some parts of the boreal region being excluded because tree canopy was < 20%. Forest fragment size also contributed to discrepancies among maps, with four of the maps specifying a minimum size. Some of the maps, for example the GIFL maps, considered that an intact forest should have a minimum size of 50,000 ha (Potapov et al. 2017). In contrast, the CIFL maps used a minimum threshold of 5,000 ha for boreal ecozones and 1,000 ha for temperate ecozones (Smith and Cheng 2016); the latter only occurred along the southern edge of the boreal region. Consequently, a greater total area of intact forests was identified by the CIFL maps. Other maps, such as the BEAD2010 and HA2010 maps did not have a minimum area requirement and consequently identified an even greater amount of intact area. Ideally, the minimum size of intact forest patches for conservation planning should be related to habitat requirements for focal species and ecological processes (Haddad et al. 2015). Consequently, conservation planners should consider minimum polygon size and map age as when evaluating the suitability of intactness data sets for their applications.

VENIER & BERNIER. Two recent papers, with relevance to the boreal context, argue for a more sophisticated approach to the assessment of the loss of ecological value from forests. In the first, Bernier et al. 2017 review the concept of "primary forest" and its use by the FAO for reporting country-level statistics. Of particular concern is the lack of a consistent operational definition resulting in substantial differences in they way primary forest areas are defined and measured within each country. They note that more recent approaches, such as Intact Forest Landscapes, provide more consistency by using satellite imagery but do not consider regional differences in ecosystem processes that can result in large differences in areas identified as intact (e.g., Lee 2009). The standard operational definition of an IFL, however, sets a minimum size threshold of 50 000 ha, which is arbitrary and disconnected from regional ecosystem processes. For example, the standard operational definition of an IFL, however, sets a minimum size threshold of 50 000 ha, which is arbitrary and disconnected from regional ecosystem processes. In the second paper, Venier et al. 2018 distinguish between conceptual and operational definitions of IFL and provide a historical review of intactness mapping, both globally and regionally. Both papers point out limitations in the criteria used to map intact areas. Specifically, the minimum size threshold of 50,000 ha is too small for wide ranging species such as caribou and wolverine and for ecosystem processes such as wildfire which can in the boreal region is considered arbitrary and not connected to regional ecosystem processes such as wildfires that can exceed 1 000 000 ha. VENIER & BERNIER

The assumed widths of human influence zones also contributed to differences in the extent of mapped intact areas. For example, the HFP maps considered up to 15-km wide zones of influence around features such as roads, major rivers and coastlines, since they are often used as transportation corridors or have high population densities. While there is plenty of evidence that human activities can have impacts beyond the point source (e.g., wolf avoidance of areas with human activities (Shepherd and Whittington 2006); use and effectiveness of riparian buffers (Richardson and Béraud 2014)), this arbitrary threshold eliminated many areas considered intact by the BEAD2010, HA2010, CIFL and GIFL maps. This may be justified in some coastal zones of Europe and more populated regions of North America, but it is not as well supported in remote areas of the northern boreal forest, where population density is negligible.

Overall, the HA2010, CIFL and GIFL maps were most similar in methodology. However, there were minor differences in the disturbance types included that resulted in relatively important differences in the areas identified as intact in some parts of the boreal region. The GIFL maps excluded burned areas near settlements. Fires play crucial roles in the dynamics of Canadian boreal forests, where most of the area burned is due to lightning-caused fires which were therefore not excluded in the CIFL maps. This alone would account for an under-estimation of 400,000 km2 of intact boreal and temperate forests in Canada by the GIFL maps (Lee 2008). Another source of disagreement was due to the treatment of rivers affected by hydroelectric power generation, which were excluded using a 1-km buffer by the GIFL maps but not by the CIFL, BEAD2010 and HA2010 maps. The use of simple buffers around disturbances, common with several maps, limits the user’s ability to use a more flexible and nuanced approach to allocating degrees of intactness within areas that have not been disturbed but are close to a disturbance. For example, when identifying reserves for species that have strong avoidance of human-impacted areas such as caribou (Environment Canada 2008), these buffers may be appropriate, and would not represent an underestimation of intact areas. However, when conservation efforts focus on less sensitive species, these buffers may be too conservative and underestimate the amount of suitable habitat. To be most flexible, future intactness mapping projects should avoid using buffers. The intactness maps also varied in the amount of area they identified as intact in the boreal region of both Canada and Alaska, likely due to differences in resolution, precision, methodology and date of input data sources. This is reflected in the inter-map comparison between the 250-m intactness maps, in which the proportion of agreement between maps in the Canadian boreal region ranged between 39-86%.

The three case studies assessed the ability of intactness maps to account for specific disturbance types in regions of the Canadian boreal forest that are currently undergoing rapid industrial development (Brandt et al. 2013, Venier et al. 2014, Geist et al. 2017, White et al. 2017). They also highlight the need to complement existing intactness maps with up-to-date high-resolution disturbance datasets to provide a more complete and detailed assessment of landscape conditions for regional conservation planning. Overall, industrial development in the boreal is occurring rapidly and even recently produced intactness maps are quickly out-of-date, suggesting the importance of updating maps on a regular basis, ideally annually. For example, linear disturbances such as seismic lines are poorly discriminated by all intactness maps. A reduction in their width over time likely resulted in some newer and narrower lines being undetected using satellite imagery (Lee and Boutin 2006, Van Rensen et al. 2015). In such cases it may be possible to identify these areas using aerial photographs or historical datasets, for example using older resources inventory maps. In the case of forest management, the more recent CIFL and GIFL maps were more effective than the other maps, identifying and removing most cutblocks from intact areas. ~~This is likely due to the shared use of 30-m Landsat imagery by those intactness maps and the two forest disturbance datasets~~. In general, the GIFL2013 map had the smallest misclassification rate among the seven maps in the Alberta and Yukon study areas, however it also identified much less intact area than the HA2010 and CIFL2013 maps. Both the CIFL2013 and GIFL2013 identified a large proportion of seismic lines and placer mining disturbances but only half of harvested areas. Note the increase in misclassification between HFP1993 and HFP2009. Surprisingly, the HA2010 map was less effective than the CIFL2013 and GIFL2013 maps at identifying all 3 disturbance types. The Human Footprint maps (HF1993, HF2009) appear to be insensitive to certain types of disturbances common in the boreal, especially seismic lines and small cutblocks, and would need to be combined with recent large-scale disturbance datasets (e.g., (Hansen et al. 2013, White et al. 2017)) to enhance their usefulness for conservation planning. The use of wide buffer zones around human activities also excludes a lot more potential intact area than do the CIFL2013 and GIFL2013 maps. However, the HF maps do allow the possibility of modifying the threshold of intactness (we used 0 as a strict cutoff) and the extent of buffer zones by manipulating the 8 underlying human footprint rasters. Two of the intactness (UNUSED, WILD) were too coarse and relied on older landcover data (GLC2000) and so were unable to reliably identify any of the recent industrial development activities. The FF map was also too coarse and out-of-date to identify disturbances post 1996.

Global maps such as GHM2015, VLIA2015, AB2000 and the HFP maps may be appropriate for broad-scale conservation planning where finer resolution data are not available. For example, this approach was used by Mittermeier et al. (Mittermeier et al. 2003) to identify and prioritize global wilderness areas. However, obtaining more detailed and up-to-date regional maps of intactness or disturbances should be a priority for any systematic conservation planning exercises, in the boreal or elsewhere. Although we are not aware of other regional intactness maps in the boreal region of Canada, there exist several examples of regional maps in other parts of the world. For example, the Human Footprint approach has been applied at regional scales in the United States (Leu et al. 2008, Woolmer et al. 2008). Other recent related initiatives have aimed at characterizing landscape patterns, forest fragmentation, and forest change at regional (Raiter et al. 2017), national (UNEP 2002, Wulder et al. 2008, Pasher et al. 2013, Guindon et al. 2014, White et al. 2017) and global scales (Hansen et al. 2013).

More recently, contextual intactness has been suggested… (Mokany et al. 2020)

Ongoing debates… (Kennedy et al. 2020, Venter et al. 2020)

## Conclusions

In general, and in comparison to the other intactness maps, the use of the CIFL (hmm), GIFL and HFP (hmm) maps are recommended since they are actively maintained, have now been developed for two points in time, use consistent methods across time, and have been partially validated with ground truth data. The BEAD2010 is probably the best dataset (2 time periods, fine scale imagery in update, but limited coverage). However, unlike the BEAD2010, HA2010, CIFL and GIFL maps, the HFP maps do not target forestry activities in the boreal and so may be more appropriate for use in the southern boreal forest where land conversion to agricultural and urban areas is more common. The choice between the BEAD2010, HA2010 or CIFL2013 maps versus the GIFL2013 maps largely comes down to 2 factors. The first is the treatment of recent fires, which in the case of the former, is treated as a natural disturbance and included in intact areas. The second is the definition of the forest zone which defines the extent of coverage of the maps. In the case of the GIFL maps, this resulted in only 86% of the Canadian boreal region being mapped versus 98% for the CIFL maps. The BEAD2010 and HA2010 maps provides more flexibility than the CIFL maps because there is no restriction on the minimum patch size. However, unlike the CIFL maps, it has not been updated since 2010. The FF1996 map is interesting from a historical perspective as it is one of the original intactness-type maps, but it is too old to be useful for either regional or national conservation planning.

The choice of map to use for broader-scale spatial conservation planning and research prioritization depends in part on the geographic location and extent of the study region. For example, an assessment of the conditions of existing protected areas in North America may select the Human Footprint maps which cover the entire region and also allow an analysis of change over time. Conversely, for the boreal region of Canada, the HA2010 and CIFL maps (and BEAD2010 in parts of the boreal) may be the best choice since they provide higher resolution data than the HFP maps for two time periods and, in contrast to the GIFL maps, they don’t consider wildfires as anthropogenic disturbances. In the case of an analysis of forest change in North America, the GIFL maps would be the best choice since they provide the most current assessment of forest intactness at a continental or global scale. Moreover, updating and improving on existing maps will result in some important cost savings. In the end, each map has strengths and weaknesses and their suitability should be judged relative to the objectives of each project.

# Supporting information

The following supplementary tables and maps are available at <https://github.com/beaconsproject/intactness>

* **S1 Fig**. Distribution of intactness datasets within the boreal region of North America. Intact areas are shown in green overlaying the boreal region in brown.
* **S2 Fig**. Cross-classification of intactness maps within the area of intersection of all datasets. Green and yellow areas indicate areas that are jointly identified as intact or non-intact, respectively.
* **S3 Fig**. Seismic lines in Alberta.
* **S4 Fig**. Forest harvesting in BC.
* **S5 Fig**. Placer mining in the Yukon.
* **S1 Table**. Description and coverage of intactness maps from Canada and Alaska.
* **S2 Table**. Examples of recent remote sensing based disturbance datasets from Canada and Alaska.
* **S1 Code**. R and Python code used to reclassify maps, estimate intactness, and calculate inter-map agreement.

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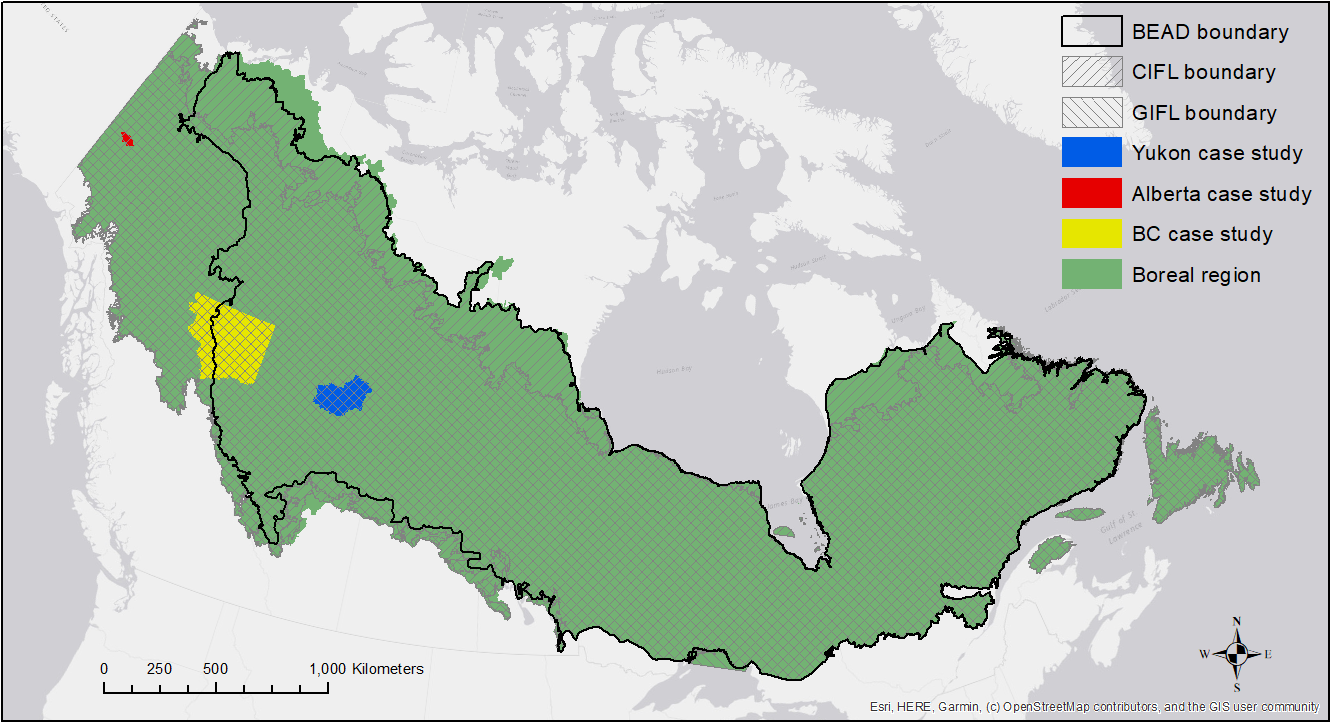
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Wulder, M. A., J. C. White, T. Han, N. C. Coops, J. A. Cardille, T. Holland, and D. Grills. 2008. Monitoring Canada’s forests. Part 2: National forest fragmentation and pattern. Canadian Journal of Remote Sensing 34:563–584.

# FIGURES

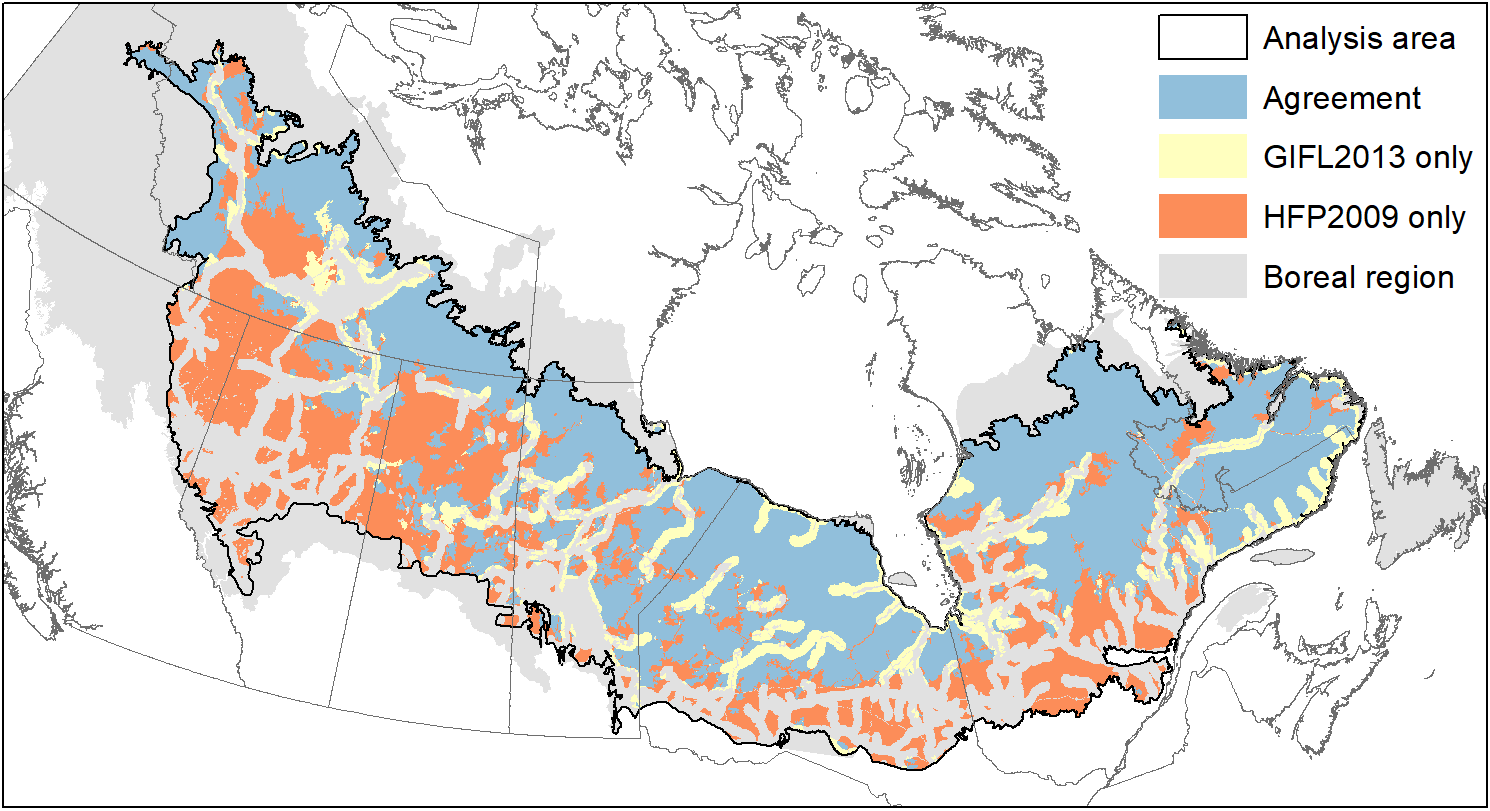
**Figure 1. Extent of boreal region in study area.** Extent of boreal region in North America, Canada, and Alberta based on Brandt's (2009) boreal and boreal alpine zones (Brandt 2009). The colored polygons indicate the location of case studies, from left to right, in Yukon, BC, and Alberta. The crosshatch pattern indicates the area of intersection of the CIFL and GIFL maps while the solid black like indicates the limits of the BEAD dataset.



**Figure 3. Distribution of disturbances and three most recent intactness maps in the case study regions.** The intactness maps are shown as a red outline (HF2009) and as green areas (GIFL2013, CIFL2013). The GIFL2013 map is shown in light green above the CIFL2013 map since its distribution is generally a subset of the CIFL2013 distribution. Only 3 intactness maps are shown in the figure to reduce the clutter; the full set of maps can be viewed in the supporting information (S4-6 Figs).

|  |  |
| --- | --- |
|  |  |
|  |  |

**Figure 3**. Spatial agreement between the GIFL2013 and HFP2009 maps. The top map indicates that 84% of the intact area identified by the HFP2009 map is also identified as intact by the GIFL2013 map. Conversely, the bottom map indicates that only 66% of the intact area identified by the GIFL2013 map is also identified as intact by the HFP2009 map.

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# TABLES

**Table 1.** General characteristics of forest intactness and human impact maps reviewed in this study.Input data sources and methodological characteristics of forest intactness and human impact maps reviewed in this study.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Dataset** | **Years1** | **Geographic extent** | **Format** | **Scale / Resolution2** | **Measurement scale** | **Buffer distance3** | **Minimum patch size** | **Reclass4** | **Thematic maps5** | **Satellite imagery** |
| Canada human access | 2010 | Canada; terrestrial ecosystems | Vector | 1:1,000,000  (~0.25 km2) | Binary; human access or not | 0.5 km | n/a | No human access = intact | Roads, mines, clearcuts, wellsites, pipelines, transmission lines, and agricultural clearings | anthropogenic disturbance layers (S2) |
| Boreal ecosystem anthropogenic disturbance | 2010, 2015 | Canada boreal; 51 caribou ranges10 | Vector | 1:50,000 | Binary; human access or not | unbuffered | n/a | No human access = intact | Hydro reservoirs (GFWC) | Landsat 5 (30-m; 2008-2010) and Landsat 8 (15- and 30-m; 2015-2017) |
| Canada intact forest landscapes | 2000, 2013 | Canadian Boreal; 11 forested ecozones | Vector | 1:1,000,000  (~0.25 km2) | Binary; intact or not intact | 1 km around roads; 0.5 km around other disturbance types | 5,000 ha boreal & taiga ecozones; 1,000 ha temperate ecozones, which occur along southern edge of Brandt’s boreal | n/a | Linear features (roads, cutlines, etc.), reservoirs, settlements; HA2010 and BEAD2010 | Landsat 5 & 7 (1988-2006; 28.5m); Landsat composite (~2013; 30m); anthropogenic disturbance layers and forest disturbance dataset (S2) |
| Global intact forest landscapes6 | 2000, 2013, 2016 | Global; forested zones - tree canopy >20% & area >4 km2 (MODIS 2000) | Vector | 1:1,000,000  (~0.25 km2) | Binary - intact or not intact | 1 km | 50,000 ha, at least 10-km wide at broadest place, at least 2-km wide in corridors | n/a | Roads, settlements, scanned topographic maps | Landsat 5 (~1990; 30m) and Landsat 7 (~2000; 30m); MODIS VCF 2000 (percent tree cover; 0.5 km2); Landsat composite (~2013; 30m) |
| Human footprint7 | 1993, 2009 | Global; terrestrial ecosystems; stratified by biomes & ecoregions | Raster | 1 km2 | Ordinal; 0-50 (low to high); sum of ranks of human pressures | Two influence zones: 0-2 km & 2-15 km | 50,000 ha | HF1993 = 0; HF2009 = 0 | 7 anthropogenic stressors (human population density, built-up area, cropland, livestock, forest cover change, roads, night-time lights) | Various including global land cover (GLC2000; 1 km2) and GlobCover 2009 (300m) |
| Anthropogenic biomes | 2000 | Global; terrestrial ecosystems | Raster | ~5 km2 | Categorical; 6 groups, 19 classes | n/a | n/a |  | 6 anthropogenic stressors (human population density, built-up area, cropland, rice area, irrigated area, pasture) | MODIS VCF 2000 (Percent Tree Cover; 0.5 km2) |
| Global human modification | 2015 | Global; terrestrial ecosystems | Raster | 1 km2 | Continuous 0-1 (low to high); proportion of landscape modified | n/a | n/a |  | 13 anthropogenic stressors (human population density, built-up area, cropland, livestock, major roads, minor roads, two-tracks, railroads, mines, oil wells, wind turbines, power lines, night-time lights) |  |
| Very low impact areas | 2015 | Global; terrestrial ecosystems | Raster | 1 km2 | Binary; 2 classes |  |  | n/a | 7 anthropogenic stressors (human population density, built-up area, cropland, livestock, forest cover change, roads, night-time lights) |  |
| Frontier forests8 | 1996 | Global; terrestrial ecosystems | Vector | 1:8,000,000  (~16 km2) | Binary; frontier or not frontier, with threat levels | n/a | Generally, > 50,000 ha | n/a | World Forest Map9 and Wilderness Areas map (McCloskey and Spalding 1989) used by > 90 experts to define large forested areas free of roads, settlements, etc. | No |

1 If the year of the dataset is not provided, we use the date of latest imagery using as input.

2 Values in brackets for vector maps indicate approximate effective grid resolution, similar to minimum mapping unit for polygonal data.

3 The distance around disturbances that is removed from the estimation of intact areas.

4 Map categories or values that were reclassified to indicate intactness.

5 Human disturbances considered by the map producers; method of detection varied by map and disturbance type and included existing maps, satellite imagery and aerial photos.

6 A key intermediate dataset was GFWC’s Canada Access 2010 dataset, which was created as the initial step in creating the IFL maps. https://globalforestwatch.ca/sites/gfwc/files/data/20140109B\_Canada\_Access\_2010\_metadata.html

7 HFP1993 is an update to the original human footprint/human influence index dataset (circa 1993) [47]

8 Frontier forests are large, ecologically intact, and relatively undisturbed natural forests [9]

9 The World Conservation Monitoring Centre, The World Forest Map, (WCMC, Cambridge, 1996).

10 Partial updates to some caribou ranges in 2012.

**Table 2.** Comparison of the areal extent of dataset coverage within the boreal region and areas identified as being intact within each dataset. See Supplementary Information for distribution maps of each map in Canada and Alaska.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Canada boreal region (5,519,764 km2)** | | | | **Alaska boreal region (737,008 km2)** | | | |
| **Dataset** | **Dataset coverage (km2)** | **Coverage of boreal (%)** | **Intact area (km2)** | **Intact area (%)** | **Dataset coverage (km2)** | **Coverage of boreal (%)** | **Intact area (km2)** | **Intact area (%)** |
| BEAD20101 | 4,371,942 | 79.2 | 4,134,336 | 94.6 |  |  |  |  |
| HA2010 | 5,394,980 | 97.7 | 4,511,406 | 83.6 |  |  |  |  |
| CIFL2000 | 5,394,980 | 97.7 | 4,029,533 | 74.7 |  |  |  |  |
| CIFL2013 | 5,394,980 | 97.7 | 3,837,668 | 71.1 |  |  |  |  |
| GIFL2000 | 4,746,030 | 86.0 | 2,780,919 | 58.6 | 475,765 | 64.6 | 379,475 | 79.8 |
| GIFL2013 | 4,746,030 | 86.0 | 2,652,463 | 55.9 | 475,765 | 64.6 | 355,012 | 74.6 |
| GIFL2016 | 4,746,030 | 86.0 | 2,619,094 | 55.2 | 475,765 | 64.6 | 350,983 | 73.8 |
| HF1993 | 5,519,764 | 100.0 | 3,867,998 | 70.1 | 737,008 | 100 | 456,736 | 62.0 |
| HF2009 | 5,519,764 | 100.0 | 3,805,526 | 68.9 | 737,008 | 100 | 455,329 | 61.8 |
| AB2000 | 5,519,764 | 100.0 | 4,752,600 | 86.1 | 737,008 | 100 | 671,113 | 91.1 |
| GHM2015 | 5,519,764 | 100.0 | 1,977,361 | 35.8 | 737,008 | 100 | 165,600 | 22.5 |
| VLIA2015 | 5,519,764 | 100.0 | 4,166,590 | 75.5 | 737,008 | 100 | 452,638 | 61.4 |
| FF1996 | 5,519,764 | 100.0 | 3,324,371 | 60.2 | 737,008 | 100 | 237,657 | 32.2 |

1 Created by erasing polygonal (231,711 km2) and 5-m buffered linear disturbances (5,894 km2). The more recent 2015 map only covers caribou ranges and was not included here.

**Table 3.** Proportional agreement between each pair-wise map comparisons within Canadian boreal region. Each entry represents the proportion of intact area in Map A (shown in the rows) that is also mapped as intact in Map B (shown in the columns). Comparisons were restricted to the area of intersection among the 9 intactness maps (3,804,654 km2).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Map 1** | | | **Map 2** | | | **Overlap** | |
| **Name** | **Intact km2** | **Unique %** | **Name** | **Intact km2** | **Unique %** | **Overlap km2** | **Overlap %** |
| bead2010 | 3,568,250 | 16.7 | ha2010 | 2,997,778 | 0.9 | 2,965,974 | 82.4 |
|  |  | 27.9 | cifl2013 | 2,573,061 | 0.1 | 2,571,254 | 72.0 |
|  |  | 43.6 | gifl2013 | 2,013,600 | 0.1 | 2,009,966 | 56.3 |
|  |  | 29.1 | hfp2009 | 2,590,171 | 2.3 | 2,507,207 | 68.7 |
|  |  | 9.2 | ab2000 | 3,392,324 | 4.5 | 3,225,463 | 86.4 |
|  |  | 59.9 | ghm2015 | 1,440,832 | 0.7 | 1,416,583 | 39.4 |
|  |  | 21.2 | vlia2015 | 2,877,688 | 2.3 | 2,792,102 | 76.4 |
|  |  | 25.0 | ff1996 | 2,715,152 | 1.5 | 2,660,976 | 73.5 |
| ha2010 | 2,997,778 | 15.8 | cifl2013 | 2,573,061 | 1.9 | 2,513,843 | 82.2 |
|  |  | 33.6 | gifl2013 | 2,013,600 | 1.2 | 1,977,164 | 65.2 |
|  |  | 22.9 | hfp2009 | 2,590,171 | 10.8 | 2,228,992 | 66.4 |
|  |  | 6.5 | ab2000 | 3,392,324 | 17.4 | 2,762,272 | 76.1 |
|  |  | 53.5 | ghm2015 | 1,440,832 | 3.2 | 1,342,443 | 43.4 |
|  |  | 16.5 | vlia2015 | 2,877,688 | 13.0 | 2,428,314 | 70.4 |
|  |  | 17.4 | ff1996 | 2,715,152 | 8.8 | 2,427,263 | 73.9 |
| cifl2013 | 2,573,061 | 22.8 | gifl2013 | 2,013,600 | 1.4 | 1,976,880 | 75.7 |
|  |  | 16.3 | hfp2009 | 2,590,171 | 16.8 | 2,069,830 | 66.9 |
|  |  | 3.6 | ab2000 | 3,392,324 | 26.9 | 2,446,047 | 69.5 |
|  |  | 46.9 | ghm2015 | 1,440,832 | 5.1 | 1,302,198 | 48.0 |
|  |  | 11.5 | vlia2015 | 2,877,688 | 20.9 | 2,199,395 | 67.6 |
|  |  | 8.0 | ff1996 | 2,715,152 | 12.8 | 2,336,362 | 79.1 |
| gifl2013 | 2,013,600 | 10.9 | hfp2009 | 2,590,171 | 30.7 | 1,698,231 | 58.4 |
|  |  | 2.2 | ab2000 | 3,392,324 | 41.9 | 1,938,490 | 55.9 |
|  |  | 40.3 | ghm2015 | 1,440,832 | 16.6 | 1,039,153 | 43.0 |
|  |  | 8.9 | vlia2015 | 2,877,688 | 36.2 | 1,734,176 | 54.9 |
|  |  | 5.0 | ff1996 | 2,715,152 | 29.5 | 1,870,605 | 65.4 |
| hfp2009 | 2,590,171 | 3.8 | ab2000 | 3,392,324 | 26.5 | 2,457,568 | 69.7 |
|  |  | 50.0 | ghm2015 | 1,440,832 | 10.1 | 1,150,103 | 39.9 |
|  |  | 14.2 | vlia2015 | 2,877,688 | 22.8 | 2,113,308 | 63.0 |
|  |  | 14.9 | ff1996 | 2,715,152 | 18.8 | 2,115,571 | 66.3 |
| ab2000 | 3,392,324 | 58.4 | ghm2015 | 1,440,832 | 2.0 | 1,371,110 | 39.6 |
|  |  | 19.9 | vlia2015 | 2,877,688 | 5.6 | 2,676,266 | 74.5 |
|  |  | 23.3 | ff1996 | 2,715,152 | 4.1 | 2,568,722 | 72.6 |
| ghm2015 | 1,440,832 | 7.3 | vlia2015 | 2,877,688 | 53.6 | 1,214,780 | 39.1 |
|  |  | 5.4 | ff1996 | 2,715,152 | 49.8 | 1,287,070 | 44.9 |
| vlia2015 | 2,877,688 | 17.2 | ff1996 | 2,715,152 | 12.3 | 2,311,793 | 70.5 |

**Table 4.** Area of seismic cutlines and 500-m buffered seismic cutlines that are wrongly classified as intact in Alberta study region (28,148.2 km2). Only cutlines that were established before map production were considered for each dataset. ABMI seismic lines are mostly polygonal features (3-m or 6-m buffer); exceptions include ABMI2016, where we added a 4.5-m buffer to create polygonal features).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Unbuffered cutlines** | | | **Buffered (500-m) cutlines** | | |
| **Intactness Map** | **Intact area (km2)** | **Intact area (%)** | **Disturbed area (km2)** | **Error (km2)** | **Error (%)** | **Disturbed area (km2)** | **Error (km2)** | **Error (%)** |
| bead2010 | 27969.3 | 99.4 | 168.8 | 116.8 | 69.2 | 47938.5 | 45833.4 | 95.6 |
| ha2010 | 23441.7 | 83.3 | 168.8 | 66.2 | 39.2 | 47938.5 | 17232.2 | 35.9 |
| cifl2013 | 20430.2 | 72.6 | 200.3 | 37.5 | 18.7 | 28718.4 | 6107.5 | 21.3 |
| gifl2013 | 14238.1 | 50.6 | 200.3 | 7.9 | 3.9 | 28718.4 | 2065.6 | 7.2 |
| gifl2016 | 13909.5 | 49.4 | 129.4 | 8.9 | 6.9 | 29613.8 | 1704.7 | 5.8 |
| hfp2009 | 23745.8 | 84.4 | 168.7 | 118 | 69.9 | 58257.2 | 50235.9 | 86.2 |
| ghm2015 | 25568.3 | 90.8 | 236.5 | 228.4 | 96.6 | 22349.1 | 20927.9 | 93.6 |
| vlia2015 | 23870.0 | 84.8 | 236.5 | 141.0 | 59.6 | 22349.1 | 17294.4 | 77.4 |

**Table 5.** Harvested cutblocks wrongly classified as intact in northeast British Columbia. Only cutblocks within 30 years of map production were considered for each dataset.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Intactness Map** | **Study area (km2)** | **Intact area (km2)** | **Intact area (%)** | **Disturbed area (km2)** | **Misclassified as intact (km2)** | **Misclassified as intact (%)** |
| BEAD2010 | 69,956.3 | 67,561.7 | 96.6 | 1,190.4 | 295.6 | 24.8 |
| HA2010 | 100,974.7 | 55,696.3 | 55.2 | 1,190.4 | 239.4 | 20.1 |
| CIFL2000 | 100,974.7 | 41,861.6 | 41.5 | 930.5 | 43.9 | 4.7 |
| CIFL2013 | 100,974.7 | 33,319.6 | 33.0 | 1,118.7 | 3.5 | 0.3 |
| GIFL2000 | 100,974.7 | 23,016.0 | 22.8 | 930.5 | 0.0 | 0.0 |
| GIFL2013 | 100,974.7 | 22,965.3 | 22.7 | 1,118.7 | 0.0 | 0.0 |
| GIFL2016 | 100,974.7 | 22,963.1 | 22.7 | 1,008.2 | 0.0 | 0.0 |
| HFP1993 | 100,974.7 | 70,818.0 | 70.1 | 608.3 | 114.1 | 18.8 |
| HFP2009 | 100,974.7 | 68,874.3 | 68.2 | 1,215.4 | 326.6 | 26.9 |
| AB2000 | 100,974.7 | 96,519.9 | 95.6 | 930.5 | 816.2 | 87.7 |
| VLIA2015 | 100,974.7 | 83,533.9 | 82.7 | 1,047.8 | 634.3 | 60.5 |
| GHM2015 | 100974.7 | 3855.6 | 3.8 | 1,047.8 | 4.6 | 0.4 |

**Table 6.** Polygonal (placer mining) and linear (mostly roads) disturbances wrongly classified as intact in the Indian River watershed, Yukon (2,257.4 km2).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Mining disturbances** | | | **Linear disturbances** | | |
| **Intactness Map** | **Intact area (km2)** | **Intact area (%)** | **Disturbed area (km2)** | **Error (km2)** | **Error (%)** | **Disturbed length (km)** | **Error (km)** | **Error (%)** |
| HA2010 | 1,723.7 | 76.4 | 64.3 | 14 | 21.8 | 1,230.1 | 467.1 | 38.0 |
| CIFL2013 | 1,095.0 | 48.5 | 64.3 | 7.7 | 12 | 1,230.1 | 261.7 | 21.3 |
| GIFL2016 | 276.8 | 12.3 | 72.2 | 0.0 | 0.0 | 1,043.8 | 19.9 | 1.9 |
| HFP2009 | 1,713.0 | 75.9 | 64.3 | 58.2 | 90.5 | 1,230.1 | 1,051.1 | 85.4 |
| VLIA2015 | 2,180.6 | 96.6 | 72.2 | 71.3 | 98.8 | 1,043.8 | 1,022.5 | 98.0 |
| GHM2015 | 110.0 | 4.9 | 72.2 | 0.1 | 0.1 | 1,043.8 | 68.2 | 6.5 |
| AB2000 | 1,861.2 | 82.4 | 64.3 | 35.3 | 54.9 | 1,230.1 | 921.7 | 74.9 |

**Table 8.** Which datasets are best for conservation planning in the boreal region of Canada?

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Map Type** | **Extent** | **Map Name** | **Years** | **Discontinued** | **Format** | **Scale/Res** | **MMU (ha)** | **Buffer (km)** | **Harvesting** | **Oil & Gas** | **Mining** | **Roads** | **Agriculture** | **Built-up** |
| Wilderness & intact areas | Global | Global IFL | 2000, 2013, 2016 |  | Vector | 1:1,000,000 | 50,000 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|  |  | Forest Frontiers | 1996 | yes | Vector | 1:8,000,000 | 50,000 |  | 0 | 0 | 0 | 0 | 0 | 0 |
|  | Regional | Canada IFL | 2000, 2013 | yes | Vector | 1:1,000,000 | 1,000; 5,000 | 0.5-1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Cumulative disturbances | Global | Human Footprint | 1993, 2009 |  | Raster | 1 km2 | 50,000 | 0-2; 2-15 | 0 | 0 | 0 | 1 | 1 | 1 |
|  |  | Human Modification | 2015 |  | Raster | 1 km2 |  |  | 0 | 1 | 1 | 1 | 1 | 1 |
|  |  | Low Impact Area | 2015 |  | Raster | 1 km2 |  |  | 1 | 0 | 0 | 1 | 1 | 1 |
|  | Regional | Human Access | 2010 | yes | Vector | 1:1,000,000 |  | 0.5 | 0 | 0 | 1 | 1 | 1 | 0 |
|  |  | BEAD | 2000, 2013 |  | Vector | 1:50,000 | 2 |  | 1 | 1 | 1 | 0 | 1 | 1 |
| Regionalizations | Global | Anthromes | 2000 |  | Raster | ~ 5 km2 |  |  | 0 | 0 | 0 | 0 | 1 | 1 |

1. Mammoth Mapping. 2010. Final Report: Mapping of surface disturbance and linear features in the Dawson Land Use Planning Region. Prepared for Environment Yukon. 7 pages. [↑](#footnote-ref-1)
2. Drift Geomatics. 2017. Review and Update Surface Disturbance Indian River Study Areas, Yukon. Submitted to Department of Environment, Government of Yukon. [↑](#footnote-ref-2)