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

Wilderness or intact areas support biodiversity, ecological and evolutionary processes including large natural disturbances, and ecosystem services such as carbon capture and sequestration [1][2][3]. They also play an important role in climate change mitigation [4][5] and can serve as ecological baselines [6]. Despite their importance and recent calls for the expansion of protected areas in wilderness or intact regions [7][8][9], the global erosion of wilderness areas exceeds the rate of protection [3]. 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, national, and regional products that attempt to map anthropogenic disturbances or their complement, areas with little or no evidence of human activities [10][11][12][13][14][15]. The maps vary in methodology, spatial and temporal characteristics, and most importantly, the area estimated to be intact. Consequently, a comparison of map products would assist conservation planners and researchers with the selection of the most appropriate product(s) to use in a given region.

Globally, boreal regions include some of the last remaining large expanses of wilderness or intact areas [16]. In North America, these areas are threatened by the rapid expansion of industrial activities such as forestry, mining, oil and gas extraction into increasingly accessible landscapes [17][18][19][20][21]. The region covers 6.3 million km2, of which 88% is in Canada and 12% is in Alaska [17]. In Canada, 8.9% of the boreal region is currently protected, with a substantial amount of that area classified as strictly protected (i.e., IUCN categories I-IV) [22][23]. There is increasing recognition of the need to expand protected areas while opportunities remain. In response, 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 [24][25]. Several major forest companies and environmental organizations have signed the Canadian Boreal Forest Agreement [26], 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 (*sensu* Arcese and Sinclair [6]), defined as areas of intact forest large enough to sustain biodiversity and support large-scale ecosystem processes such as fire with minimal external inputs [27][13][28][16]. For example, intact areas are often favoured 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 [29][30].

In the boreal region where forests dominate the landscape, wilderness or intact areas have much in common with the concept of intact forest landscapes [31] (Box 1). Intact areas become non-intact through the accumulation of human impacts such as road construction, logging, mining, and urban development. Maps that measure intactness can be used along with other information to evaluate the sustainability of forest management [32][33], monitor trends in biodiversity and other forest resources [34][35][36][37], assess the effectiveness of conservation strategies [38][39], and inform conservation planning and policy decisions [40][41][1]. 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 [42] with implications for forest management policies [43].

Several global and national maps have been developed that can be used to identify intact areas in the boreal region of North America. 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. The availability of a broad range of 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 three specific anthropogenic disturbances common in the boreal region: oil and gas exploration in Alberta, logging in British Columbia, and mining in the Yukon. Our goal is to inform conservation planning in one of the world’s remaining wilderness areas.

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| **BOX 1. Mapping wilderness and intact areas**  Several initiatives have attempted to map the world’s last remaining large wilderness or intact areas in the past 30 years. All have relied on the use of existing maps and satellite imagery to identify areas with little or no human disturbances. We briefly review four initiatives, three of which we compare in this paper, in order of chronology.  *Wilderness Areas*. The World Wilderness Areas map was the first global initiative that attempted to map areas with little or no human influence [11]. To qualify, areas had to be ≥ 4,000 km2 after eliminating all areas within 6 km of human infrastructures e.g., roads and settlements. More recently, the IUCN has used the term wilderness to describe “landscapes and seascapes that are biologically and ecologically largely intact, with a low human population density and that are mostly free of industrial infrastructure” [44]. The minimum size for inclusion is 10,000 km2 with human densities of ≤ 5 people per km2 and retaining at least 70% of historical habitat extent [2].  *Frontier Forests*. The Frontier Forests initiative attempted to map the world’s remaining large intact natural forests, which the authors defined as forests that are “relatively undisturbed and big enough to maintain all of their biodiversity, including viable populations of the wide-ranging species associated with each forest type” (pp. 12) [10]. Similar to wilderness areas, human disturbances due to traditional activities are considered acceptable. No explicit minimum size for inclusion was specified. The concept has been questioned for its utility for identifying high priority conservation areas because of the methods and criteria used to define intact forests [45].  *Last of the Wild*. The Last of the Wild was derived from the human footprint map [12], an initiative which, in contrast to the other initiatives, focused on assessing the levels of human activity and not on the identification of intact areas. However, it was subsequently used to identify the least disturbed areas within each biome, by reclassifying all areas with a human influence index of ≤ 10 to represent areas with little or no disturbances. In this paper, we used more recent versions of the human footprint maps [46] and considered human index values of 0 as representing intact areas.  *Intact Forest Landscapes*. Intact forest landscapes [13] are defined 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” ([www.intactforest.org](http://www.intactforest.org)). The working definitions include criteria related to minimum size, type and buffer width of disturbances (Tables 1 and 2). The specific definition in Canada diverges from the global definition with respect to some of the criteria, for example the treatment of fires (see Discussion). |

# Methods

## Study area and map products

Our study area comprises the spatial extent of the boreal and boreal alpine regions (i.e., the boreal region) of Canada and Alaska [47] (Figure 1). We selected 10 commonly used national and global maps that are freely available in a GIS format and that, at a minimum, covered a large portion of the region. All maps are global in extent except for the three developed by Global Forest Watch Canada for the Canadian boreal and temperate forests. The maps can be broadly categorized into four groups. Five of the maps use similar methods to measure intactness as the absence of a conspicuous anthropogenic disturbance: Frontier Forests (FF) map for 1996 produced by the World Resources Institute [10]; Global Forest Watch’s (GFW) global intact forest landscapes (IFL) maps for the years 2000 and 2013 (GIFL2000 and GIFL2013) [13][16]; and GFW Canada’s (GFWC) IFL maps for the years 2000 and 2013 (CIFL2000 and CIFL2013) [48][49]. All maps buffer disturbances except for FF. GFW IFL maps include wildfires occurring near infrastructure as an anthropogenic disturbance. Three maps were developed by mapping cumulative human pressures on terrestrial ecosystems: Human Footprint maps for the years 1993 and 2009 (HF1993 and HF2009) [46][50] and Canada’s Human Access map for 2010 (HA2010) [51]. Two other maps classify the earth into homogeneous regions or zones, including undisturbed zones: Wilderness and Unproductive Areas (UNUSED) map for 2000 derived from the Human Appropriation of Net Primary Production (HANPP) project [52][53] and the wildland classes (WILD) from the Anthropogenic Biomes map for 2000 [54][55].

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, and rasterized or resampled to a 1-km2 resolution. No information was lost when resampling to a smaller cell size. We then reclassified the maps, if necessary, to binary intactness maps, with 1 indicating little or no human impact and 0 identifying non-intact areas (Table 1). For the human footprint maps (HF1993 and HF2009), all areas with no human influence (HF=0) were assigned a value of 1 while remaining areas (HF > 0) were assigned a value of 0. Similarly, for the HA2010 map we assigned a value of 1 to all pixels that were not identified as human access areas. For the frontier forest map (FF), all frontier forest polygons were assigned a value of 1, irrespective of their threat level. In the case of the WILD map, we reclassified the two wildland biomes from the Anthropogenic Biomes map to 1 and all other biomes to 0. For the UNUSED map, all pixels without land use in the HANNP Unused map were assigned a value of 1. Following map reclassifications, we calculated, for each map, the geographical coverage of the mapped product within the boreal regions of Canada and Alaska, and the total area identified as intact.

We estimated the area of spatial agreement and disagreement between the 1-km2 intactness maps using geospatial analyses performed in ArcGIS 10.4 [56] and the raster package [57] in R 3.41 [58] (S1 Code). For the CIFL, GIFL and HF maps, we used the most recent map only for a total of 21 comparisons. We restricted the spatial extent of the analysis to the intersection of the 7 intactness maps (Figure 1). We then constructed a contingency table, also known as an error or confusion matrix, to summarize the results.

## Regional assessments

We conducted three case studies to assess the ability of each intactness map to account for specific disturbance types, and the benefits of using high-resolution regional data sources to create a more complete assessment of current landscape conditions (Figure 3, Table 5). The case studies focused on oil and gas exploration in Alberta, forest harvesting in British Columbia, and placer mining in the Yukon. For each intactness map in each study area, we calculated the total area that was erroneously classified as being intact. Estimates were based on removing disturbed areas only, not buffered areas as used by some intactness maps (i.e., CIFL, GIFL, and HF maps); consequently, estimates for those maps are conservative.

The first case study is from northern Alberta, where oil and gas exploration has expanded at a rapid pace in recent decades, leading to a proliferation of seismic lines across the landscape [59][60]. To identify seismic lines, we used the high-resolution human footprint index maps (HFI) developed by the Alberta Biodiversity Monitoring Institute [61]. The HFI maps consist of 1:15,000 vector polygons which map the distribution of 24 anthropogenic disturbances related to energy extraction, forestry, agricultural, and human settlements. The HFI is produced approximately every two years (2007, 2010, 2012, and 2014) using a variety of field data, aerial photography and high-resolution satellite imagery [61]. We used HFI2012 to evaluate CIFL2013 and GIFL2013, the HFI2010 to evaluate the HA2010, and HFI2007 to evaluate HF2009. We did not evaluate the other maps due to their large temporal disconnect with the earliest HFI map produced. Prior to the analysis, we converted the raster intactness maps to polygonal shapefiles. We then intersected each intactness map with the HFI2007, HFI2010 and HFI2012 datasets and tabulated the area of the seismic line footprint type that was located within areas identified as intact.

The second case study consists of an area in northeast British Columbia where forest harvesting has been occurring for the past decades. We used the C2C Forest Change (C2C) and Canada Landsat Disturbance (CanLaD) datasets [62][63] to evaluate how well the intactness maps captured and removed recent cutblocks (1985-2011 for C2C and 1985-2015 for CanLaD). Both datasets were developed from 30-m Landsat imagery to map changes due to forest fires and harvesting in Canada's forested ecozones [64], making them suitable to evaluate this aspect of intactness. We focused on stand replacing harvested areas, of which two types are mapped in the C2C dataset: harvest and lower-confidence harvest. The distinction is made to indicate that some change events were more difficult to allocate to a change type, but are generally found to be in the correct category [62]. We only used the former category in our analyses. Both datasets consist of two key maps, forest change type and forest change year, which we combined to create maps showing the location and year of harvest areas within the study region. We then used the vectorized versions of the intactness maps, clipped to the study area, to calculate the areal extent of harvested areas within areas identified as intact. Depending on the age of the intactness map, we removed harvest areas that occurred post map production. Finally, we dropped 1985 harvest pixels since there was a large discrepancy between the 2 datasets that could be due to Landsat scene selection at the beginning of the time series or other methodological differences i.e., the starting point of the 2 datasets may have been off by a few months resulting in additional disturbances in one dataset.

The third case study is from central Yukon Territory near the Alaska border 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. The study area consists of two watersheds selected to represent areas with numerous streams and rivers that are actively being mined for gold. We used the recently produced Northwest Boreal LCC Anthropogenic Footprint mining dataset [65] to identify placer mines. As with the other two case studies, we intersected the vectorized versions of the intactness maps with the mining footprint map to identify areas that were erroneously mapped as being intact. Unlike the other two case studies, there was no time attribution to the mining dataset and, consequently, as with the Alberta case study we dropped the older intactness maps from the analysis to minimize the potential overestimation of errors in those datasets.

# Results

## Map characteristics

Seven of the 10 maps that we evaluated have global or near-global extents, the exceptions being the national-scale CIFL and HA2010 maps (Tables 1 and 2). Map resolutions varied from relatively fine (CIFL, GIFL and HA2010 effective resolution ≈ 0.25 km2) to relatively coarse (UNUSED and WILD map resolution ≈ 86 km2). The 10 maps 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 FF map, satellite imagery was used to map forested areas and identify 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 [66]. Data production methods differed with respect to study area delineation and minimum mapping unit. For example, minimum patch size for the HF 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. 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 Anthropogenic Biomes map used cluster analysis to identify and map zones based on factors such as human population density, land use and land cover. Two of the resulting 19 zones were labeled as wildlands (WILD): wild woodlands and wild treeless and barren lands.

## Intactness estimates and agreement

All maps except for the CIFL and the GIFL maps covered 100% of the boreal region of Canada and Alaska as defined by Brandt [47] (Table 3, S1 Fig). The CIFL maps were restricted to the Canadian boreal region, covering 98% of the region. The GIFL maps covered 86% and 65% of the boreal region of Canada and Alaska, respectively. In Canada, the total area identified as intact within each map, ranged from 56% for the GIFL2013 map to 83% for the HA2010 map. The CIFL maps identified 16.1% and 15.2% more intact area in 2000 and 2013, respectively, than the GIFL maps. For the three maps produced in 2 different years (HF, CIFL, and GIFL), the most recent maps identified between 1.2% and 3.6% less intact area. In Alaska, the area identified as intact ranged more widely than in Canada: from 32% for the FF map to 84% for the WILD map. The GIFL2013 map identified 5.2% less intact area than the GIFL2000 map while the difference between the HF2009 and HF1993 maps was only 0.4%.

Pixel-level agreement between maps varied from a high of 99% (HA2010 vs CIFL2013 and GIFL2013) to a low of 59% (GIFL1013 vs WILD; Table 4, Figure 2, S3 Fig). The highest agreement was between the HA2010 map and both the GIFL2013 and CIFL2013 maps, where 99% of the CIFL2013 and GIFL2013 is present in the HA2010 map. In contrast only 85% and 68% of the HA2010 map is present in the CIFL2013 and GIFL2013 maps, respectively. This is not surprising since the HA2010 map identifies significantly more intact landscapes than the CIFL2013 and GIFL2013 maps. A similar pattern occurred between the GIFL2013 and CIFL2013 maps, where 98% of the GIFL2013 map is present in the CIFL2013 map but only 79% of the CIFL2013 map is present in the GIFL2013 map. This discrepancy is also related to the fact that the CIFL2013 map identifies > 800,000 km2 more intact landscapes than the GIFL2013 map. Even though inter-map agreement is relatively high, it is important to also consider the total area of disagreement; in this case, 43,652 km2 of the GIFL2013 map is not classified as intact by the CIFL2013 map while 685,641 km2 of the CIFL2013 map is not classified as intact by the GIFL2013 map. The lowest agreement was between the WILD and GIFL2013 maps, where only 59% of the WILD map was present in the GIFL2013 map. This corresponds to an area of 1.6 million km2 that is in disagreement. Overall, there was relatively high inter-map agreement (i.e., ≥80%) in half of the 42 comparisons.

## Regional assessments

*Seismic lines in Alberta*. Most of the seismic lines occurred in the southern half of the study area and were established prior to 2007 (S4 Fig). Between 2007 and 2012, an additional area of only 2 km2 was created. All intactness maps were relatively poor at accounting for seismic lines, probably because they are difficult to detect without aerial photos (Figure 3, Table 5a, S4 Fig). The GIFL2013 and CIFL2013 maps erroneously classified 18% and 48% of seismic lines as intact, respectively. The difference 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). The HF2009 failed to identify the majority of seismic lines (92%), with the exception of a few in the northwest that were removed by the placement of a buffer around the navigable Peace river.

*Forest harvesting in British Columbia*. The total area identified as having been harvested by the two disturbance datasets, C2C and CanLaD, was very similar when all years were combined (Table 5b1-b2 and S5 Fig). The CIFL2013, GIFL2013, and HA2010 maps were relatively effective at identifying and removing cutblocks from intact areas, especially in comparison to the CanLaD dataset, with only 0-6% of harvested areas retained in the intactness maps. The areas wrongly classified as intact were somewhat higher using the C2C dataset, ranging from 8 to 13% of the total area harvested. The other datasets, HF2009, FF, UNUSED and WILD, were poor at identifying and removing cutblocks from intact areas, with 22-96% of harvested areas retained in the intactness maps. For example, the lower elevation Peace River valley in the southern half of the study area has been extensively logged more recently (1995-2005) and this is reflected in the CIFL2013, GIFL2013, HF2009, and UNUSED maps but not the FF and WILD maps.

*Placer mining in the Yukon*. Over-estimation of intactness varied greatly in the Yukon study area, ranging from 4% for the GIFL2013 map to 44% for the HF2009 map. Interestingly, both of those maps also estimated the least amount of the study area as being intact (51% and 55%, respectively) in comparison to the HA2010 and CIFL2013 maps (89% and 80%, respectively). Other maps were more moderate in over-estimating intactness. The CIFL2013 and GIFL2013 maps both removed many but not all placer mine footprints (Table 5c and S6 Fig). The CIFL2013 map omits approximately three times as much area as the GIFL2013 map. The HF2009 map removes 44% of mining disturbance areas, specifically those that are within a buffer distance of roads and navigable rivers.

# Discussion

There is growing interest in conserving intact forests [3][8][9] prior to land conversion and natural resource development [17][19]. 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 [19][39][20]. 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 [3][8][38][48], but there is no universally accepted means to measure it over large extents. We compared 10 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 48% (GIFL2013) to 83% (HA2010) in Canada and 32% (FF) to 84% (WILD) in Alaska. 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 [66].

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 UNUSED and WILD 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 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) [62]. 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 [22][25].

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 FF and CIFL maps is due to the delineation of the FF 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 [16]. In contrast, the CIFL maps used a minimum threshold of 5,000 ha for boreal ecozones and 1,000 ha for temperate ecozones [49]; 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 HA2010 map 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 [67]. Consequently, conservation planners should consider minimum polygon size and map age as when evaluating the suitability of intactness data sets for their applications.

The assumed widths of human influence zones also contributed to differences in the extent of mapped intact areas. For example, the HF maps (and, by association, the UNUSED map) 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 [68]; use and effectiveness of riparian buffers [69]), this arbitrary threshold eliminated many areas considered intact by the HA201, 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 [66]. 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 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 [70], 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 1 km2 intactness maps, in which the proportion of agreement between maps in the Canadian boreal region ranged between 59-99%.

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 [17][19][62][65]. 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 [59][60]. 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 CIFL2013, GIFl2013 and HA2010 maps were much 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 omission 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. 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., [14][62]) 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 HF, UNUSED and WILD 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. [2] 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 GIFL methodology has also been applied at regional and national scales to map remaining intact forest landscapes in Russia [71], Alaska [72], and Venezuela [73]. Similarly, the Human Footprint approach has been applied at regional scales in the United States [74][15]. Other recent related initiatives have aimed at characterizing landscape patterns, forest fragmentation, and forest change at regional [75], national [35][33][76][77][62] and global scales [14].

## Conclusions

In general, and in comparison to the other intactness maps, the use of the CIFL, GIFL and HF 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. However, unlike the HA2010, CIFL and GIFL maps, the HF maps does 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 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 CIF maps. The HA2010 map 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 FF 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 UNUSED has some overlap with HF2009 but is less complete and uses older input datasets.

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 may be the best choice since they provide higher resolution data than the HF 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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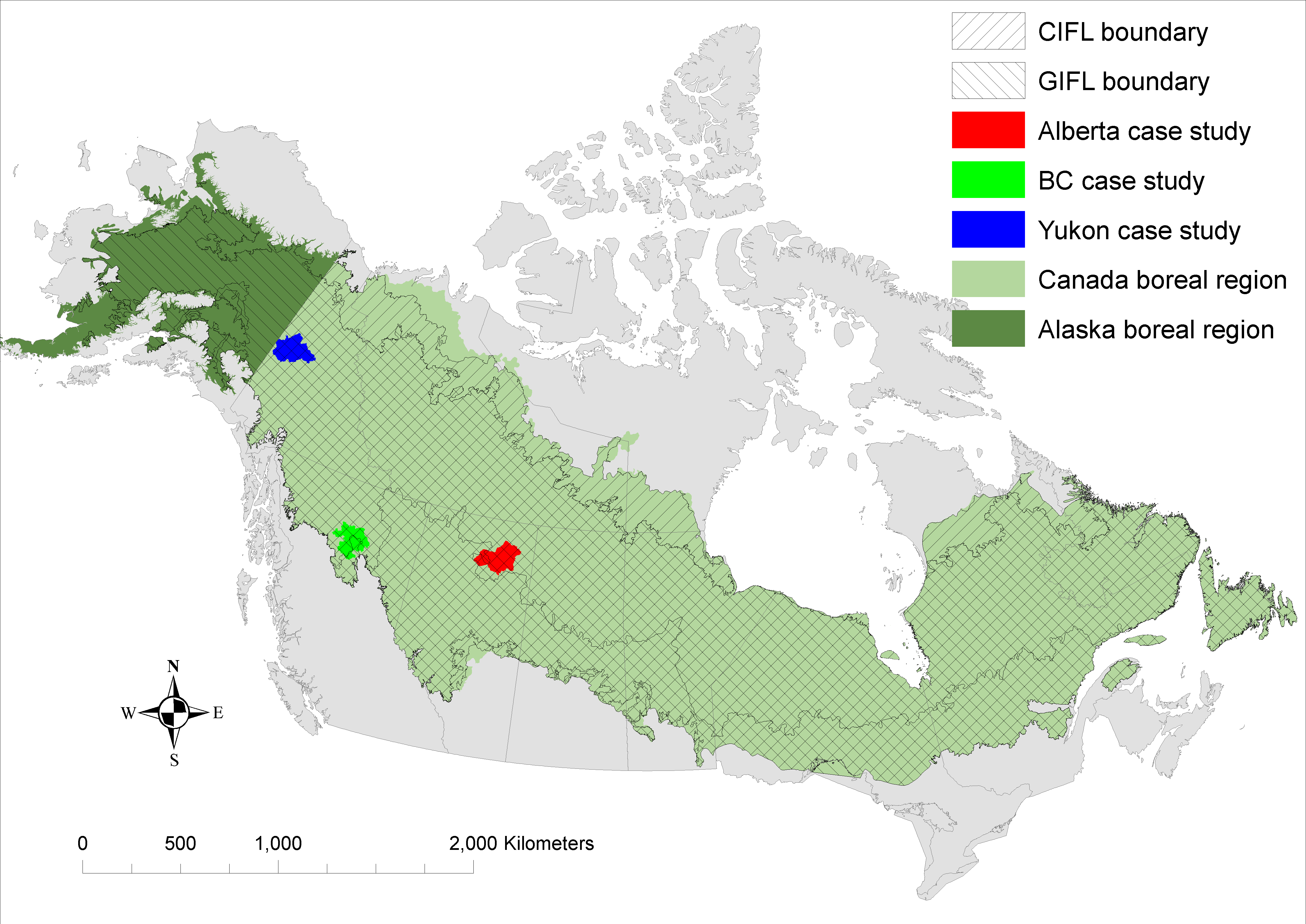
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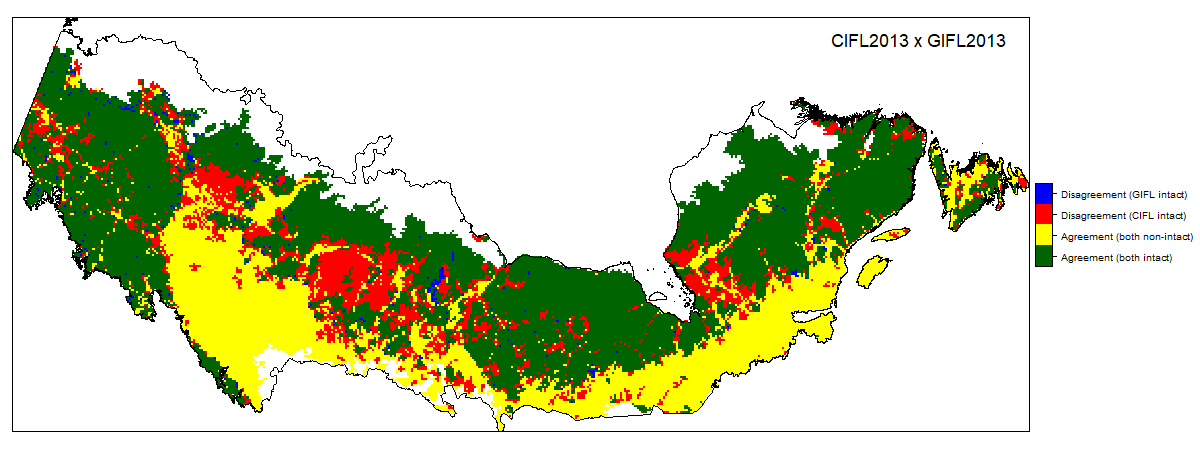
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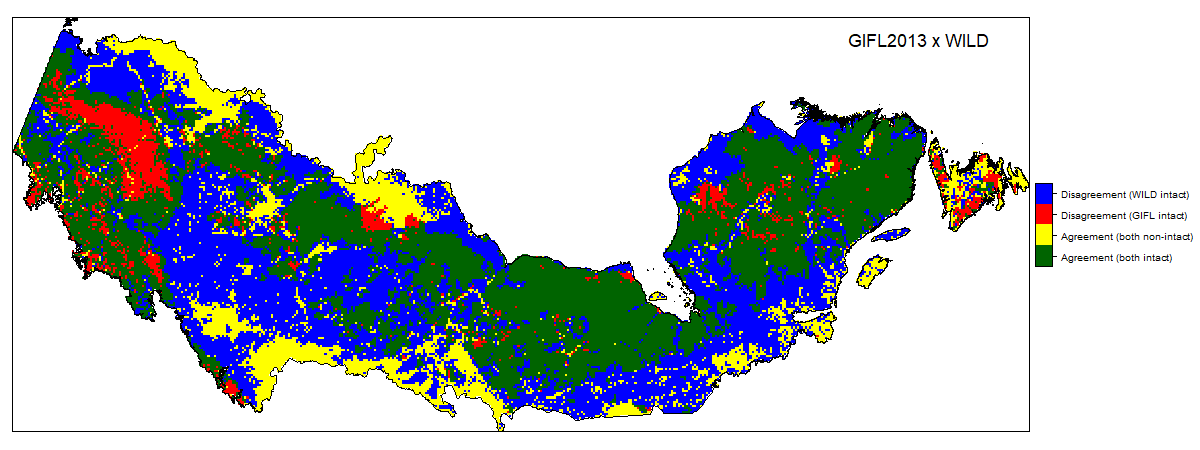
# FIGURES

**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 [47]. The colored polygons indicate the location of case studies, from left to right, in Yukon, BC, Alberta, and Quebec. The crosshatch pattern indicates the area of intersection of the CIFL and GIFL maps and, by extension, all 10 intactness maps.

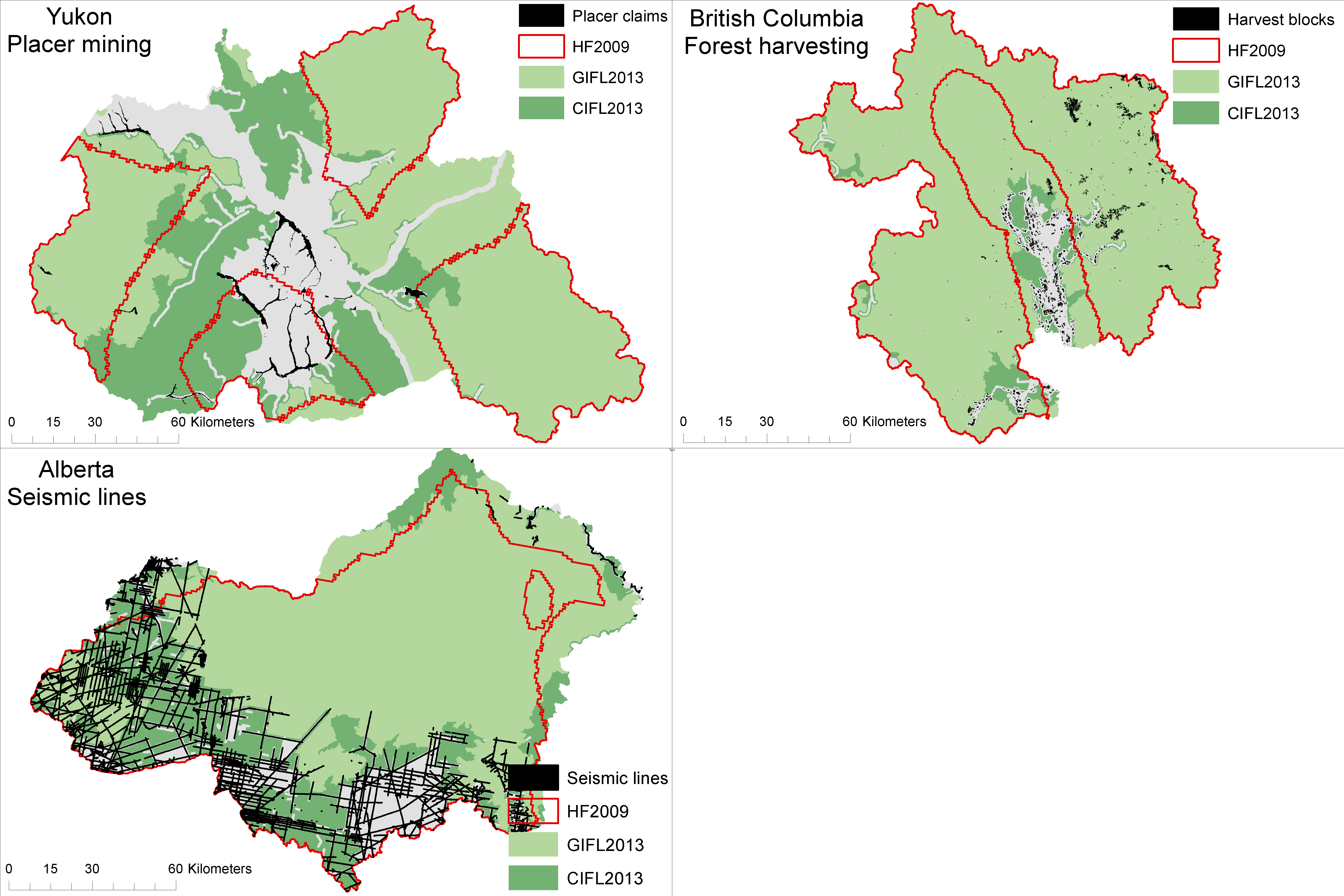


**Figure 2. Cross-classification of intactness maps**. Cross-classification of CIFL2013 x GIFL2013 and GIFL2013 x WILD maps within the area of intersection of all datasets. Green and yellow areas indicate areas that are jointly identified as intact or non-intact, respectively. The full set of maps can be found in S3 Fig.





**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).



# TABLES

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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Map** | **Title and version/year1** | **References** | **Format** | **Geographic extent** | **Resolution2** | **Measurement scale** | **Reclass3** |
| HA2010 | Canada Human Access (2010) | [51] | Vector | Canada; terrestrial ecosystems | 1:1,000,000 (~0.25 km2) | Binary - human access or not | No human access = intact |
| CIFL2000, CIFL2013 | Canada intact forest landscapes4 (2000, 2013) | [49, 32] | Vector | Canadian Boreal; forested ecozones (Ecological Stratification Working Group 1996) | 1:1,000,000 (~0.25 km2) | Binary - intact or not intact | Not needed |
| GIFL2000, GIFL2013 | Global intact forest landscapes  (2000,2013?) | [11, 33] | Vector | Global; forested zones | 1:1,000,000 (~0.25 km2) | Binary - intact or not intact | Not needed |
| HF1993, HF2009 | Human footprint5  (1993, 2009) | [47, 48] | Raster | Global; terrestrial ecosystems | 1 km2 | Interval - sum of ranks of 8 human pressures (0-50) | HF1993 = 0; HF2009 = 0 |
| FF | Frontier Forests6  (1996) | [9] | Vector | Global; terrestrial ecosystems | 1:8,000,000 (~16 km2) | Binary - frontier or not frontier, with attribute assessing threat level from low or no threat (1) to medium or high threat (3) | Not needed |
| UNUSED | Areas with no land use (2000) | [53, 52] | Raster | Global; terrestrial ecosystems | 5 arc minutes (~86 km2 at equator) | Ratio - proportion of cell without land use (0-100) | 100% without land use |
| WILD | Anthropogenic biomes (v. 2) (2000) | [54, 55] | Raster | Global; terrestrial ecosystems | 5 arc minutes (~86 km2 at equator) | Categorical - 19 biomes including wild woodlands | wild woodlands; wild treeless & barren lands |

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 (CIFL and GIFL) indicate approximate effective grid resolution [78], similar to minimum mapping unit for polygonal data. To make the maps comparable, we rasterized the CIFL and GIFL vector maps to 1 km2 and resampled the FF, UNUSED, and WILD raster maps to 1 km2.

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

4 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

5 HF1993 is an update to the original human footprint/human influence index dataset (circa 1993) [47]

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

**Table 2.** Input data sources and methodological characteristics of forest intactness and human impact maps reviewed in this study.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Map** | **Thematic maps** | **Satellite imagery** | **Study area delineation** | **Minimum patch size** | **Human disturbances1** | **Buffer distance2** |
| HA2010 | Linear features (roads, cutlines, etc.), reservoirs, agricultural croplands | anthropogenic disturbance layers (S2) | Canada | n/a | Roads, mines, clearcuts, wellsites, pipelines, powerlines, transmission lines, agricultural clearings, etc. | 0.5 km |
| CIFL2000, CIFL2013 | Linear features (roads, cutlines, etc.), reservoirs, settlements | Landsat 5 & 7 (1988-2006; 28.5m); Landsat composite (~2013; 30m); anthropogenic disturbance layers and forest disturbance dataset (S2) | Canada's 11 forested ecozones [62]) | 5,000 ha boreal & taiga ecozones; 1,000 ha temperate ecozones, which occur along southern edge of Brandt’s boreal | Roads, seismic lines, transmission lines, mines, hydroelectric stations, logged areas, agriculture, settlements, etc. | 1 km around roads; 0.5 km around other disturbance types |
| GIFL2000, GIFL2013 | 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) | Tree canopy >20% & area >4 km2 (MODIS 2000); WWF ecoregions | 50,000 ha, at least 10-km wide at broadest place, at least 2-km wide in corridors | Roads, settlements, waterways, pipelines, powerlines, agriculture, cutblocks, logging, mines, oil & gas (focus on 30-70 years), burned areas near settlements | 1 km |
| HF1993, HF2009 | Population density, land transformation, land access, electrical power infrastructure | Various including global land cover (GLC2000; 1 km2) and GlobCover 2009 (300m) | Terrestrial ecosystems; stratified by biomes, ecoregions to create HFP map | 50,000 ha | Settlements, roads, railways, roads, major rivers, coastlines, reservoirs, dams | Two influence zones: 0-2 km & 2-15 km |
| FF | World Forest Map3 and Wilderness Areas map [11] used by > 90 experts to define large forested areas free of roads, settlements, etc. | No | Terrestrial ecosystems | Generally, > 50,000 ha | n/a | n/a |
| UNUSED | FAO, country-level land use statistics, Human Footprint | Global land cover 2000 (GLC2000; 1 km2) | Terrestrial ecosystems | ~86 km2 | Human Footprint | n/a |
| WILD | Population density (LandScan 2005; 0.86 km2); Land use (2000-2005; 0.86 km2); | MODIS VCF 2000 (Percent Tree Cover; 0.5 km2) | Terrestrial ecosystems | 1 km2 | n/a | n/a |

1 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.

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

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

**Table 3.** Comparison of the areal extent of dataset coverage and areas identified as being intact within the boreal region1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Dataset** | **% Area Coverage of Boreal Region** | | **% Area of Boreal Intact** | | **% Area of Boreal Intact within dataset coverage** | |
|  | Alaska | Canada | Alaska | Canada | Alaska | Canada |
| HA2010 | n/a | 100.0 | n/a | 82.7 | n/a | 82.7 |
| CIFL2013 | n/a | 97.7 | n/a | 69.5 | n/a | 71.1 |
| CIFL2000 | 0.0 | 97.7 | n/a | 73.0 | n/a | 74.7 |
| GIFL2013 | 64.6 | 86.0 | 48.2 | 48.1 | 74.6 | 55.9 |
| GIFL2000 | 64.6 | 86.0 | 51.5 | 50.4 | 79.8 | 58.6 |
| HF2009 | 100.0 | 100.0 | 62.5 | 68.9 | 62.5 | 68.9 |
| HF1993 | 100.0 | 100.0 | 62.9 | 70.1 | 62.9 | 70.1 |
| FF | 100.0 | 100.0 | 32.2 | 60.2 | 32.2 | 60.2 |
| UNUSED | 100.0 | 100.0 | 57.8 | 58.9 | 57.8 | 58.9 |
| WILD | 100.0 | 100.0 | 83.6 | 79.2 | 83.6 | 79.2 |

1 The spatial extent of the North American boreal region is 6,256,692 km2 (5,519,907 km2 in Canada and 736,785 km2 in Alaska)[47]

**Table 4.** Proportional agreement between each of the 21 pair-wise map comparisons. 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). Similarly, the value in brackets represents the area in km2 in Map A that is not classified as intact by Map B. Comparisons were restricted to the area of intersection among the 7 intactness maps (4,732,465 km2).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **HA2010** | **CIFL2013** | **GIFL2013** | **HF2009** | **FF** | **UNUSED** | **WILD** |
| **HA2010** | 1 | 0.99 (16532) | 0.99 (24406) | 0.89 (367572) | 0.92 (258442) | 0.92 (230584) | 0.84 (629384) |
| **CIFL2013** | 0.85 (574182) | 1 | 0.79  (685641) | 0.80  (669197) | 0.80  (658352) | 0.72  (933048) | 0.87  (425531) |
| **GIFL2013** | 0.68 (1224045) | 0.98  (43652) | 1 | 0.84  (436118) | 0.81  (504849) | 0.76  (626985) | 0.87  (352841) |
| **HF2009** | 0.73 (1022522) | 0.82  (571897) | 0.69  (980807) | 1 | 0.74  (821857) | 0.76  (754562) | 0.87  (408038) |
| **FF** | 0.72 (1068856) | 0.87  (405588) | 0.71  (894074) | 0.78  (666393) | 1 | 0.72  (845888) | 0.91  (259167) |
| **UNUSED** | 0.65 (1362616) | 0.87  (358666) | 0.74  (694592) | 0.90  (277480) | 0.81  (524270) | 1 | 0.89  (302384) |
| **WILD** | 0.85 (586505) | 0.74  (1026060) | 0.59  (1595359) | 0.72  (1105867) | 0.71  (1112460) | 0.62  (1477295) | 1 |

**Table 5.** Disturbed areas wrongly classified as intact by intactness maps in three case study areas within the boreal forest: (a) seismic line areas in northern Alberta, (b1 & b2) recently harvested areas in northeast British Columbia, and (c) placer mining areas in west central Yukon.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Intactness Map** | **Study area (km2)** | **Intact area (km2)** | **Intact area (%)** | **Disturbed area (km2)** | **Area wrongly classified as intact (km2)** | **Area wrongly classified as intact (%)** |
| **(a) Alberta – Seismic lines** | | | | | | |
| HA2010 | 22192 | 20087 | 91 | 32 | 17 | 53 |
| CIFL2013 | 22192 | 18410 | 83 | 33 | 13 | 38 |
| GIFL2013 | 22192 | 14086 | 63 | 33 | 6 | 18 |
| HF2009 | 22192 | 18800 | 85 | 31 | 29 | 92 |
| **(b1) British Columbia – Forest harvesting (C2C dataset)** | | | | | | |
| HA2010 | 19981 | 18824 | 94 | 204 | 26 | 13 |
| CIFL2013 | 19981 | 18597 | 93 | 206 | 16 | 8 |
| GIFL2013 | 19981 | 17502 | 88 | 206 | 16 | 8 |
| HF2009 | 19981 | 15809 | 79 | 204 | 56 | 27 |
| FF | 19981 | 13441 | 67 | 104 | 88 | 85 |
| UNUSED | 19981 | 17488 | 88 | 146 | 40 | 27 |
| WILD | 19981 | 17524 | 88 | 146 | 139 | 96 |
| **(b2) British Columbia – Forest harvesting (CanLaD dataset)** | | | | | | |
| HA2010 | 19981 | 18824 | 94 | 204 | 11 | 6 |
| CIFL2013 | 19981 | 18597 | 93 | 204 | 2 | 1 |
| GIFL2013 | 19981 | 17502 | 88 | 204 | 1 | 0 |
| HF2009 | 19981 | 15809 | 79 | 203 | 44 | 22 |
| FF | 19981 | 13441 | 67 | 116 | 99 | 85 |
| UNUSED | 19981 | 17488 | 88 | 149 | 31 | 21 |
| WILD | 19981 | 17524 | 88 | 149 | 143 | 95 |
| **(c) Yukon – Placer mining** | | | | | | |
| HA2010 | 20695 | 18448 | 89 | 227 | 45 | 20 |
| CIFL2013 | 20695 | 16561 | 80 | 227 | 27 | 12 |
| GIFL2013 | 20695 | 11357 | 55 | 227 | 10 | 4 |
| HF2009 | 20695 | 10593 | 51 | 227 | 100 | 44 |