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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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North America's boreal forest contains some of the largest remaining intact and wild ecosystems in the world. However, human activities are systematically reducing its extent. Consequently, forest intactness and human influence maps are increasingly used for monitoring and conservation planning in the boreal region. We evaluated nine national and global maps to determine how well they agreed with each other and how effectively they captured recent anthropogenic disturbances. As a function of each map's spatial coverage in North America, the area identified as intact ranged from 55 to 79% in Canada and from 32 to 96% in Alaska. Likewise, the similarity between pairs of datasets in the Canadian boreal ranged from 0.58 to 0.86 on a scale of 0–1. In total, 45% of the region was identified as intact by the eight most recent datasets. There was also variation in the ability of the datasets to account for anthropogenic disturbances that are increasingly common in the boreal region, such as those associated with resource extraction. In comparison to the recently produced high resolution Boreal Ecosystem Anthropogenic Disturbance dataset, the four human influence datasets (Human Footprint, Global Human Modification, Large Intact Areas, and Anthropogenic Biomes) omitted 59–85% of all linear disturbances and 54–89% of all polygonal disturbances. In contrast, the global IFL, Canadian IFL, and Human Access maps omitted 2–7% of linear disturbances and 0.1–5% of polygonal disturbances. Several differences in map characteristics, including input datasets and methods used to develop the maps may help explain these differences. Ultimately, the decision on which dataset to use will depend on the objectives of specific conservation planning projects, but we recommend using datasets that (1) incorporate regional anthropogenic activities,

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(2) are updated regularly, (3) provide detailed information of the methods and input data used, and (4) can be replicated and adapted for local use. This is especially important in landscapes that are undergoing rapid change due to development and have an active natural disturbance regime, such as the boreal forest of North America.

Keywords: intact forest landscapes, human footprint, boreal forest, conservation planning, anthropogenic disturbances, accuracy assessment

INTRODUCTION

North America's boreal forest contains some of the largest remaining intact areas 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 their 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; Carroll and Noss, 2020) and can serve as ecological benchmarks to guide sustainable land management practices (Arcese and Sinclair, 1997). Moreover, they are homelands to many Indigenous peoples, whose long-term stewardship has maintained the critical functions these areas support (e.g., Sobrevila, 2008; Schuster et al., 2019). Despite their importance and recent calls for the expansion of protected areas in intact or wilderness regions (Betts et al., 2017; Dinerstein et al., 2017; Tilman et al., 2017), their global erosion has exceeded their rate of protection (Watson et al., 2016). To identify and conserve additional intact areas, reliable and up-to-date spatial information is required. This has led to the production of 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 et al, 1997; Sanderson et al., 2002; Potapov et al., 2008; Hansen et al., 2013). The maps vary in methodology, spatial and temporal characteristics, and most importantly for the purposes of this paper, the area estimated to be intact in the boreal region. A quantitative comparison of these maps would assist conservation planners and researchers with the selection of the most appropriate product(s) for their purposes.

The boreal region of North America covers 6.3 million km^2, of which 88% is in Canada and 12% is in Alaska (Brandt et al., 2013). In Canada, 11.4% of the region is currently under some form of protection (CPCAD 2019). In Canada, and globally, there is increasing recognition of the need to expand protected areas while opportunities remain. The United Nations Convention on Biological Diversity developed a set of goals (the "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 committed to setting aside 50% of the boreal region of each province in various levels of protection to safeguard against anticipated future resource development [Government of Quebec (Minister of Natural Resources and Wildlife), 2009; OMNR, 2013]. Intact areas are also being considered as a policy instrument in forest conservation and management and have recently been integrated into the certification standards of the Forest Stewardship Council (FSC, 2015). More generally, intact areas, whether protected or not, can serve as benchmarks 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). The forests and peatlands of the boreal region also are important carbon sinks [but see Zhao et al. (2021)] and the maintenance of intact areas may be part of a natural solution to carbon sequestration and CO_2 reduction (Griscom et al., 2017). Consequently, intact areas have an important role to play in the design of protected area networks that could achieve the Aichi Targets and the targets of national or regional governments.

Several global and regional initiatives have attempted to map the overall condition of the world's ecosystems in the past 30 years (**Table 1**). The initiatives can be divided into two broad groups based on their primary objective: intactness mapping and human influence mapping. Intactness is considered to be a structural descriptor of landscapes that reflects the absence of anthropogenic disturbances as measured from thematic maps (e.g., of roads) or from remote sensing data (Wulder et al., 2008). An area becomes non-intact through the accumulation of human impacts, often related to resource extraction activities such as logging, mining, oil and gas development, and their associated roads. The intactness mapping approach attempts to map remaining areas with little or no human activities by removing anthropogenic disturbances that are detectable using satellite imagery and other input data; sometimes buffers are applied to detected features to account for their presumed zones of influence. Remaining areas are considered free from significant human pressures. In contrast, the human influence mapping approach combines multiple disturbance layers into an overall map of disturbance intensity. 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 (McCloskey and Spalding, 1989). To qualify, areas had to be $\geq$ 4,000 km^2 after eliminating all areas within 6 km of human infrastructures e.g., of roads and settlements. Subsequently, the Frontier Forests initiative, produced by the World Resources Institute, also attempted to map the world's remaining large intact forests (Bryant et al, 1997). No explicit minimum size

TABLE 1 | General characteristics of intactness and human influence maps reviewed in this study including geographic extent, format, resolution, measurement scale, buffer distance, minimum patch size, and sources of input data (i.e., thematic maps and satellite imagery).

Dataset	Years[1]	Geographic extent	Format	Scale/ Resolution[2]	Measurement scale	Buffer distance[3]	Minimum patch size of intact area	Thematic maps[4]	Satellite imagery[4]
Frontier forests (FF)	1996	Global; terrestrial ecosystems	Vector	1:8,000,000 (~16 km^2)	Binary; frontier or not frontier, with threat levels	n/a	Generally, >50,000 ha	World Forest Map and Wilderness Areas map (McCloskey and Spalding, 1989) used by > 90 experts to define large forested areas free of roads, settlements, etc.	No
Canada human access (HA)	2010	Canada; terrestrial ecosystems	Vector	1:1,000,000 (~0.25 km^2)	Binary; human access or not	0.5 km	n/a	Roads, mines, clearcuts, wellsites, pipelines, transmission lines, and agricultural clearings	Anthropogenic disturbance layers
Boreal ecosystem anthropogenic disturbance (BEAD)	2010, 2015	Canada boreal; 51 boreal caribou ranges	Vector	1:50,000	Binary; human access or not	Unbuffered	n/a	Hydro reservoirs (GFWC)	Landsat 5 (30-m; 2008–2010) and Landsat 8 (15- and 30-m; 2015–2017)
Canada intact forest landscapes (CIFL)	2000, 2013	Canadian Boreal; 11 forested ecozones	Vector	1:1,000,000 (~0.25 km^2)	Binary; intact or not intact	1 km around highways; 0.5 km around other disturbance types	5,000 ha boreal and taiga ecozones; 1,000 ha temperate ecozones, which occur along southern edge of Brandt's boreal	Linear features (roads, cutlines, etc.), reservoirs, settlements; Canada human access (GFWC)	Landsat 5 & 7 (1988–2006; 28.5 m); Landsat composite (~2013; 30 m); anthropogenic disturbance layers and forest disturbance dataset
Global intact forest landscapes (GIFL)	2000, 2013, 2016	Global; forested zones – tree canopy >20% & area >4 km2 (MODIS 2000)	Vector	1:1,000,000 (~0.25 km^2)	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	Roads, settlements, scanned topographic maps	Landsat 5 (~1990; 30m) and Landsat 7 (~2000; 30m); MODIS VCF 2000 (percent tree cover; 0.5 km^2); Landsat composite (~2013; 30 m)
Human footprint (HFP)	2000, 2005, 2010, 2013	Global; terrestrial ecosystems; stratified by biomes & ecoregions	Raster	1 km^2	Ordinal; 0–50 (low to high); sum of ranks of human pressures	Two influence zones: 0–2 km & 2–15 km	50,000 ha	Human population density, built-up area, cropland, livestock, forest cover change, roads, night-time lights	Various including global land cover (GLC2000; 1 km^2) and GlobCover 2009 (300 m)
Canadian human footprint (CHFP)	2019	Canada	Raster	300-m	Ordinal; 0–50 (low to high); sum of ranks of human pressures	Variable within and by disturbance type	n/a	Similar to global HFP with addition of Canada Gov't data on mining, oil and gas	Landsat-based 30-m forest harvest data (White et al., 2017)

(Continued)

TABLE 1 | (Continued)

Dataset	Years[1]	Geographic extent	Format	Scale/ Resolution[2]	Measurement scale	Buffer distance[3]	Minimum patch size of intact area	Thematic maps[4]	Satellite imagery[4]
Anthropogenic biomes (Anthromes, AB)	2000, 2005, 2010, 2015	Global; terrestrial ecosystems	Raster	~5 km²	Categorical; 6 groups, 19 classes	n/a	n/a	Human population density, built-up area, cropland, rice area, irrigated area, pasture	MODIS VCF 2000 (Percent Tree Cover; 0.5 km²)
Global human modification (GHM)	2016	Global; terrestrial ecosystems	Raster	1 km²	Continuous 0–1 (low to high); proportion of landscape modified	n/a	n/a	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 (VLIA)	2015	Global; terrestrial ecosystems	Raster	1 km²	Binary; 2 classes			Human population density, built-up area, cropland, livestock, forest cover change, roads, night-time lights	

References and links to all datasets are provided in the ***Supplementary Material****. Note that we also describe the BEAD dataset which was used to assess the accuracy of the other datasets.*
[1]If the year of the dataset is not provided, we use the date of latest imagery used as input.
[2]Values in brackets for vector maps indicate approximate effective grid resolution, similar to minimum mapping unit for polygon data.
[3]The distance around disturbances that is removed from the estimation of intact areas.
[4]A more complete list of thematic maps and satellite imagery used as inputs can be found within the references listed for each dataset.

was specified and, like wilderness areas, human disturbances due to traditional Indigenous activities did not disqualify areas. In the boreal region where forests dominate the landscape, ideas of wilderness or intact areas have much in common with the concept of the Intact Forest Landscape (IFL), 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" (Potapov et al., 2008). Potapov et al.'s (2008) definition was an effort to more fully to operationalize the concept of Frontier Forests. Global Forest Watch (GFW) developed global maps of IFLs which were delineated using specific criteria related to minimum size, patch width, and corridor width (Potapov et al., 2008, 2017). These maps were produced for the years 2000, 2013 and 2016. The IFL mapping approach has also been applied at a regional scale in Canada for the years 2000 and 2013 by GFW Canada (Lee et al., 2010; Smith and Cheng, 2016). Although similar in approach, the national and global IFL maps differ with respect to some criteria, for example the size of buffers and the treatment of wildfires (Lee, 2009).

Among the human influence mapping approaches, one of the most well-known is the Human Footprint (HFP; Venter et al., 2016). It provides a standardized measure of cumulative human pressures on the environment based on the extent of built environments (e.g., urban areas), crop land, pasture land, human population density, night-time lights, railways, roads and navigable waterways (Sanderson et al., 2002). The HFP has been updated several times while adhering to consistent methods, with the most recent dataset current to 2013 (Venter et al., 2016; Williams et al., 2020). All versions of the HFP can be reclassified to identify areas with little or no disturbances. Another well-known dataset is the Anthropogenic Biomes (Anthromes) map (Ellis and Ramankutty, 2008) that classifies the terrestrial biosphere into 19 categories based on human interactions with ecosystems, including agriculture, urbanization, forestry and other land uses. It also has been updated, with the most recent version current to 2015 (Ellis et al., 2020). For all versions, the most relevant categories for mapping intact areas are the wildland categories (i.e., wild woodlands, wild treeless and barren lands). Two more recent datasets, the (Very) Low Impact Areas map (Jacobson et al., 2019) and the Global Human Modification map (Kennedy et al., 2019) also provide a cumulative measure of human modification of terrestrial lands across the world for the years 2015 and 2016, respectively. Both approaches are similar to the HFP approach but differ in the number and types of input anthropogenic stressor datasets, and the methods to calculate human influence (Riggio et al., 2020). At regional extents, GFW Canada also developed the Human Access dataset for 2010 as an intermediary step to creating the Canada IFL 2013 map (Lee and Cheng, 2014). The dataset maps recent linear and areal disturbances related to resource extraction but, unlike the IFL datasets, does not use a minimum size criterion. More recently, a Canadian version of the Human Footprint map was developed that incorporates disturbances not included in the global version, such as those associated with resource extraction (Hirsh-Pearson et al., 2021).

A recent study comparing the four human influence maps at the global scale found that, despite differences in methods and data, they produced similar estimates of the percentage of terrestrial ecosystems having low and very low human influence (Riggio et al., 2020). The purpose of this study is to assess the relative suitability of the currently available intactness and human influence maps for conservation planning in the boreal region of Canada. Our specific objectives were:

1. To compare intactness estimates across the boreal region of Canada and Alaska;
2. To quantify inter-map variability and identify areas of agreement among multiple maps;
3. To assess the accuracy of the maps against independent and higher resolution data mapping anthropogenic disturbances common in the boreal region, such as forest harvesting, oil and gas exploration, roads, and mining; and
4. To illustrate some of the mapping issues in more detail using two case studies. The first describes the effectiveness of intactness and human influence maps at identifying disturbances related to mining in west-central Yukon, Canada. The second evaluates the sensitivity of intactness estimates to details of mapping methodology (e.g., buffer widths and minimum patch size) in northern Alberta, Canada.

MATERIALS AND METHODS

Our overall study area comprises the spatial extent of the boreal and boreal alpine regions of North America (Brandt, 2009). However, most of our analysis is focused on a large subset (86%) of the Canadian boreal region (**Figure 1**, black outline), representing the intersection of the intactness and human influence maps evaluated. We acquired nine open access national and global intactness and human influence maps (**Table 1**), of which six were global and three were regional in extent. Two of the regional maps, produced by GFW Canada, covered only Canada's boreal and temperate forests. The third map, the Canadian Human Footprint map, covered the spatial extent of Canada. Four of the maps were produced for more than 1 year, for a total of 17 maps-years. **Table 1** summarizes the map characteristics and mapping methodology.

Intactness Estimates and Spatial Agreement

We converted all maps to an Albers Equal Area projection and clipped them to the boreal region of Canada and Alaska. Raster maps were vectorized. We then reclassified or recoded maps, based on the map legends, to create a set of binary intactness maps (**Table 2**). Values of 1 indicate intact areas having little or no human influence. Values of 0 indicate non-intact areas. We refer to each binary intactness map by an alphanumeric code based on the "dataset" and "years" columns in **Table 1**. The Canadian and global intact forest landscape maps (CIFL2000-13, GIFL2000-16) did not need to be reclassified. For the Human Footprint maps (HFP2000-13, CHFP2019) and very low impact areas map (VLIA2015), all areas with little or no human influence (map values of 0) were recoded as 1 (intact) while all other areas were recoded as 0. For the global human modification map (GHM2016), we followed Riggio et al. (2020) and assigned pixels with values ranging from 0 to 0.01 a value of 1. For the HA2010 map, we eliminated all disturbance polygons from the boreal study region and assigned a value of 1 to the resultant areas. For the frontier forest map (FF), all polygons were assigned a value of 1 irrespective of their threat level. For the anthropogenic biome maps (AB2000-15), we assigned a value of 1 to the wildland categories (i.e., wild forest, sparse trees and barren). We then calculated, for each map, the proportional area of the boreal region identified as intact. This calculation was restricted to the area of each maps' intersection within the boreal region (**Figure 1**). For Canada, we estimated intactness using all datasets. For Alaska, the Canadian HFP and GFW Canada datasets were necessarily excluded.

To evaluate the spatial agreement of datasets, we first converted all original datasets to the same format (raster) and resolution (1-km^2), and then aligned them to a common grid by resampling. We restricted the spatial extent of the analysis to the area of intersection of all datasets. For the Canada IFL, Global IFL and HFP maps, we used the most recent annual maps. The Frontier Forests map was excluded because of its age and low original resolution. We quantified the area of spatial agreement (i.e., pairwise similarities) between the maps using Jaccard's similarity coefficient (Fewster and Buckland, 2001). The Jaccard coefficient measures the similarity between datasets and is defined as the area of intersection of two datasets divided by the area of union. Values for the coefficient range from 0 (complete dissimilarity) to 1 (complete similarity). To better visualize and quantify the amount and spatial pattern of overlap between the eight binary intactness maps, we created a composite map showing areas estimated to be intact by only one map, two or more maps, and all eight maps.

Accuracy Assessment

The third objective of this study was to assess how well the binary intactness maps account for the specific anthropogenic disturbances that are common in the boreal region, namely those associated with fossil fuel exploration and extraction, forestry, and mining. To do this, we used the Boreal Ecosystem Anthropogenic Disturbance (BEAD) dataset (Pasher et al., 2013) updated to 2015. This is a high spatial resolution dataset that was derived from 30- and 15-m resolution Landsat 8 imagery. It was created specifically to identify disturbances in and around woodland caribou (*Rangifer tarandus caribou*) ranges (**Figure 1**, hatched area). Two broad disturbance types were mapped within each range: (1) linear disturbances such as roads, seismic cutlines, and pipelines, and (2) polygonal disturbances such as forest cutblocks, agricultural areas, and mining quarries. The dataset includes both buffered and unbuffered linear and polygonal disturbances, covering 4.4

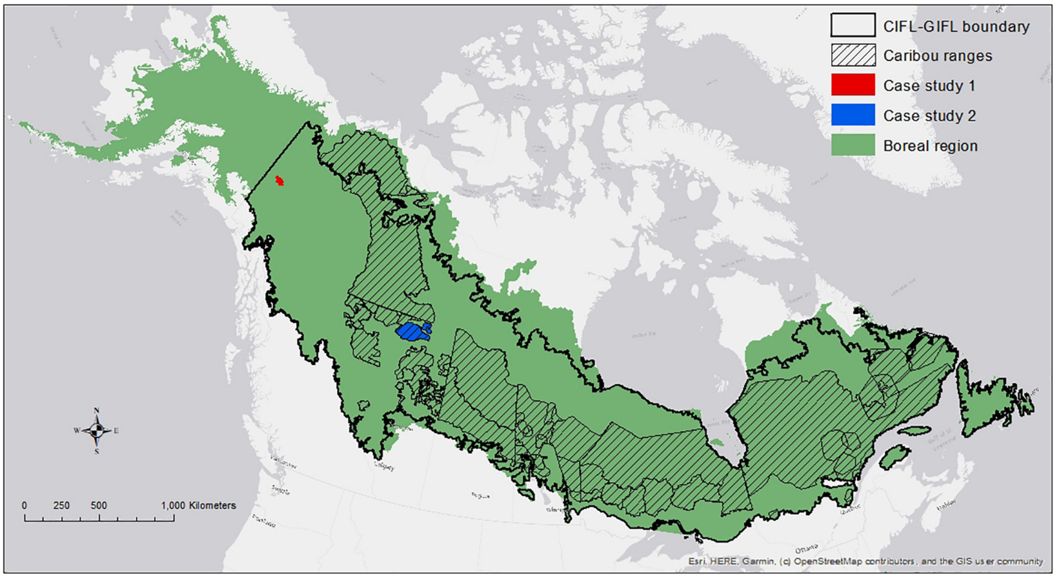

FIGURE 1 | Extent of boreal region, including boreal and boreal alpine zones, in North America (Brandt, 2009). The solid black line indicates the area of intersection of the eight intactness and human influence maps while the crosshatch pattern indicates the limits of the 51 caribou ranges that make up the 2015 BEAD dataset (Pasher et al., 2013). The locations of case studies 1 and 2 are indicated by the red and blue polygons, respectively.

million km^2 of the boreal encompassing 51 caribou ranges. We used the unbuffered BEAD data to evaluate the eight most recent binary intactness maps: HA2010, Canada IFL2013, Global IFL2016, HFP2013, CHFP2019, AB2015, VLIA2015, and GHM2016. For each caribou range, we estimated the proportion of linear and polygonal disturbance types that were identified by BEAD but omitted by the binary intactness maps using the vectorized version of the maps. These estimates are conservative because no buffer was applied to the disturbances.

Case Studies

The two case studies provide additional assessments of the binary intactness maps. In the first case study, we assess the accuracy of the maps at identifying disturbances related to placer mining, the technique of recovering gold from gravel along streams and rivers, in west-central Yukon (**Figure 1**). We used the same methods described in the previous paragraph but with a reference dataset consisting of linear and polygon disturbances associated with placer mining (Mammoth Mapping, 2010; Drift Geomatics, 2017). In the second case study, we evaluate the sensitivity of intactness estimates to differences in buffer size around disturbances and minimum intact patch size in one caribou range located in northern Alberta (**Figure 1**). For buffer size, we evaluated no buffers, 500 m buffers, and 1,000 m buffers around anthropogenic disturbances. To keep the analysis simple, we applied the same buffer width to both linear and polygonal disturbances. Similarly, for minimum intact patch size, we used no minimum size, a 50 km^2 minimum, and 500 km^2 minimum. All analyses in the main text and the cases studies were conducted using R 4.0.3 (R Core Team, 2020) and the sf (Pebesma, 2018) and raster (Hijmans, 2020) packages.

RESULTS

Intactness Estimates and Spatial Agreement

All binary intactness maps except for the GIFL maps (GIFL2000-16) covered at least 98% of the boreal region of Canada (Brandt, 2009) (**Table 3**). The three GIFL maps covered 86% of the region. The total area identified as intact within the spatial extent of each map, ranged from 55 to 59% for the three GIFL maps to 89% for the four AB maps (AB2000-15). The amount identified by the GHM2016, HA2010, and the five HFP maps (CHFP2019, HFP2000-13) were very similar, ranging from 79 to 84%. In contrast, the FF1996 map was relatively low, with only 60% of the boreal identified as intact. The remaining maps ranged between 71 and 76% for VLIA2015 and CIFL maps (CIFL2000-13), respectively. Among multi-temporal datasets, the CIFL2013 map identified 3.6% less intact forest than the CIFL2000 map, while the GIFL2016 map identified 3.4% less intact area than the GIFL2000 map. In contrast, the reduction in intact area between the newest and oldest HFP and AB maps was only 0.3 and 0.1%, respectively. In Alaska, the area identified as intact varied more widely than in Canada, ranging from 32% for the FF1996 map to 96% for the GHM2016 map (**Table 3**). The four GIFL maps identified 19–21% more intact area in Alaska than in Canada with a 6% reduction between the oldest and newest maps. In contrast, the AB2000-15 and HFP2000-13 maps indicated little change in the proportion of intact areas over time, similar to Canada.

Pairwise spatial agreement between binary intactness maps ranged from a low of 0.58 between the GIFL2016 and VLIA2015 maps to a high of 0.86 between the AB2015, GHM2016 and CHFP2019 maps (**Table 4**). The GIFL2016 map stood out as

TABLE 2 | GIS procedures used to derive “intactness” maps. Map abbreviations are used in the text to refer to the names of the intactness and reclassified human influence maps.

Dataset	Map abbreviations	Procedure used to create “intactness” maps
Frontier forests	FF1996	No procedure required
Canada human access	HA2010	Erased human access polygons from boreal region
Canada intact forest landscapes	CIFL2000, CIFL2013	No procedure required
Global intact forest landscapes	GIFL2000, GIFL2013, GIFL2016	No procedure required
Human footprint	HFP2000, HFP2005, HFP2010, HFP2013, CHFP2019	Assigned a value of 1 to pixels with value = 0; converted to vector map
Anthropogenic biomes	AB2000, AB2005, AB2010, AB2015	Assigned a value of 1 to pixels with values = 61, 62, 63; converted to vector map
Very low impact areas	VLIA2015	Assigned a value of 1 to pixels with value = 0; converted to vector map
Global human modification	GHM2016	Assigned a value of 1 to pixels with values = 0–0.01; converted to vector map

being least similar to all other maps except for CIFL2013. The similarity between the GIFL2016 and CIFL2013 maps was 0.77 while with all other maps it was 0.67 or less. Most other paired comparisons ranged between 0.70 and 0.85, indicating a relatively high degree of similarity. The composite map of the eight binary intactness maps revealed that 45% of the study region was identified as intact by all eight maps with an additional 17% identified by at least seven of the maps (**Figure 2**). Only 3% of the study region was identified as disturbed (not intact) by all eight maps.

Accuracy Assessment

The area identified as intact within the 51 caribou ranges included in the BEAD data, by the eight binary intactness maps, ranged from 45% for the GIFL2016 map to 93% for the AB2015 map (**Table 5**). There were 31% more linear disturbances identified with the 15-m BEAD data than with the 30-m BEAD data. Most of the differences were due to seismic lines (41% more) and roads (22% more). In contrast, there was only 0.2% more polygonal disturbances identified with the 15-m data than with the 30-m data. Overall, the binary intactness maps can be divided into two broad groups based on their relative accuracy. The human influence group, consisting of HFP2013, CHFP2019, AB2015, VLIA2015 and GHM2016, omitted 59–85% of all linear disturbances and 28–89% of all polygonal disturbances. In contrast, the forest intactness group, consisting of GIFL2016, CIFL2013, and HA2010, omitted between 2 and 7% of linear disturbances and 0.1–5% of polygonal disturbances. The most common linear anthropogenic disturbances in the study area were seismic cutlines, roads, pipelines, and powerlines. Railways, airstrips, and dams also occurred, but to a much lesser extent. In general, the binary intactness maps in the human influence group omitted all linear disturbance types much more (49–74% on average) than those in the forest intactness group (0–8% on average). The VLIA2015 map omitted all disturbance types more often than any other map. The HFP2013 and CHFP2019 maps were the only binary intactness maps in the human influence group that had some omission rates below 20%, specifically for railways and dams. In the human influence group, omission of seismic lines ranged from 62% by the AB2015 map to 89% by the VLIA2015 map. This compares to 2–7% for the maps in the forest intactness group. Roads, pipelines, and powerlines were also omitted 37–81% of the time by the maps in the human influence group compared to 0–8% for those in the forest intactness group. Among the maps in the forest intactness group, the CIFL2013 and GIFL2016 performed best, omitting only 2–4% of seismic lines and roads, respectively. Only dams were omitted more than 10% of the time, by the HA2010 and CIFL2013 maps. The GIFL2016 map never exceed an omission rate of 5% while the HA2010 consistently omitted more linear disturbances than CIFL2013 and GIFL2016.

By far, the most common and widely distributed anthropogenic polygonal disturbances in the study area were forest cutblocks, followed by agriculture, settlements, and mines. Well sites and other oil and gas infrastructure also occurred to a much lesser extent. In general, and as with linear disturbances, the binary intactness maps in the human influence group omitted all polygonal disturbance types more than those in the forest intactness group, 8–64% on average compared to 0.2–2%. In particular, cutblocks were omitted 29–91% of the time by the maps in the human influence group. This compares to 0.1–5% for the maps in the forest intactness group. Mines and well sites were also more often omitted by binary intactness maps in the human influence group. Among those, the HFP2013 map had the lowest omission rate for all polygonal disturbance types except for well sites and cutblocks. Cutblocks were the one polygonal disturbance type where CHFP2019 had a lower omission rate than HFP2013. Both CIFL2013 and GIFL2013 never exceeded a 1% omission rate for any polygonal disturbance type. Similar to the linear disturbances, the HA2010 map had higher omission rates than the two IFL maps, although it never exceeded 5%.

The use of higher resolution test data (i.e., BEAD) was most noticeable with linear disturbances, with 68 and 28% seismic lines and roads identified, respectively. This had much larger impact on the maps in the forest intactness group, roughly doubling the omission rates of roads for HA2010, CIFL2013 and GIFL2013 and of seismic lines for HA2010 and CIFL2013. Even with these increases, however, the overall omission rates for all linear disturbances for CIFL2013 and GIFL2013 was less than 6.5%. In contrast, the omission rates for the binary intactness maps in the human influence group did not change much but remained much higher than for those in the forest intactness group.

Case Studies

The first case study evaluates the effectiveness of the binary intactness maps at identifying disturbances related to placer mining in west-central Yukon. Among the 8 datasets we analyzed, the GIFL2016 map omitted the least amount of both

TABLE 3 | Comparison of the areal extent of dataset coverage within the boreal region and areas identified as being intact within each dataset.

Dataset	Canada boreal region (5,519,764 km^2)				Alaska boreal region (737,008 km^2)			
	Dataset coverage (km^2)	Coverage of boreal (%)	Intact area (km^2)	Intact area (%)	Dataset coverage (km^2)	Coverage of boreal (%)	Intact area (km^2)	Intact area (%)
HA2010	5,519,764	100.0	4,565,591	82.7				
CIFL2000	5,394,980	97.7	4,029,533	74.7				
CIFL2013	5,394,980	97.7	3,837,668	71.1				
CHFP2019	5,519,764	100.0	4,385,428	79.4				
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
HFP2000	5,519,764	100.0	4,474,868	81.1	737,008	100.0	614,217	83.3
HFP2005	5,519,764	100.0	4,481,331	81.2	737,008	100.0	614,444	83.4
HFP2010	5,519,764	100.0	4,466,114	80.9	737,008	100.0	613,338	83.2
HFP2013	5,519,764	100.0	4,464,139	80.9	737,008	100.0	613,685	83.3
AB2000	5,519,764	100.0	4,919,781	89.1	737,008	100.0	645,668	87.6
AB2005	5,519,764	100.0	4,919,588	89.1	737,008	100.0	645,668	87.6
AB2010	5,519,764	100.0	4,921,931	89.2	737,008	100.0	645,668	87.6
AB2015	5,519,764	100.0	4,918,939	89.1	737,008	100.0	645,427	87.6
GHM2016	5,519,764	100.0	4,627,206	83.8	737,008	100.0	707,686	96.0
VLIA2015	5,519,764	100.0	4,166,590	75.5	737,008	100.0	690,993	93.8
FF1996	5,519,764	100.0	3,324,371	60.2	737,008	100.0	237,657	32.2

*See **Supplementary Material** for distribution maps of each map in Canada and Alaska.*

TABLE 4 | Proportional agreement between each pair-wise map comparisons within Canada's boreal region measured using Jaccard's similarity coefficient.

Map	HA2010	CIFL2013	GIFL2016	HFP2013	CHFP2019	AB2015	GHM2016	VLIA2015
HA2010	1							
CIFL2013	0.85	1						
GIFL2016	0.67	0.77	1					
HFP2013	0.81	0.79	0.65	1				
CHFP2019	0.80	0.76	0.62	0.86	1			
AB2015	0.80	0.73	0.59	0.84	0.86	1		
GHM2016	0.81	0.77	0.62	0.83	0.86	0.86	1	
VLIA2015	0.74	0.70	0.58	0.75	0.79	0.77	0.84	1

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 eight datasets (4,732,303 km^2).

linear and polygonal anthropogenic disturbances (0.0 and 1.9%, respectively; **Table 6**). However, it identified only 12% of the study region as being intact, far less than the CIFL2013 and HFP2013 maps which identified 49 and 55% of the area as intact, respectively. Three of the datasets, VLIA2015, GHM2016 and AB2015, identified 92–96% of the area as being intact and, consequently had very high rates of omission, ranging from 66 to 95% for linear disturbances and 88–98% for polygonal disturbances. The other two datasets, CIFL2013 and HA2010 omitted a moderate amount of both polygonal (12 and 22%, respectively) and linear (21 and 38%, respectively) disturbances. The second case study consists of a simple two factor analysis conducted in northern Alberta to illustrate the sensitivity of intactness estimates to buffer size around anthropogenic disturbances and minimum intact patch size. The results indicate that the area estimated to be intact varies from 44 to 98% depending on buffer size and minimum intact patch area, with buffer size having a larger influence than minimum patch size (**Figure 3**). Interactive maps of the two case study regions are available in the **Supplementary Material**.

DISCUSSION

The boreal region of North America is experiencing rapid industrial development (Brandt et al., 2013; Venier et al., 2014; White et al., 2017). Consequently, there is a need for reliable and up-to-date information on changes in ecosystem conditions. To that end, we compared nine global and regional maps depicting intactness or cumulative human influence on

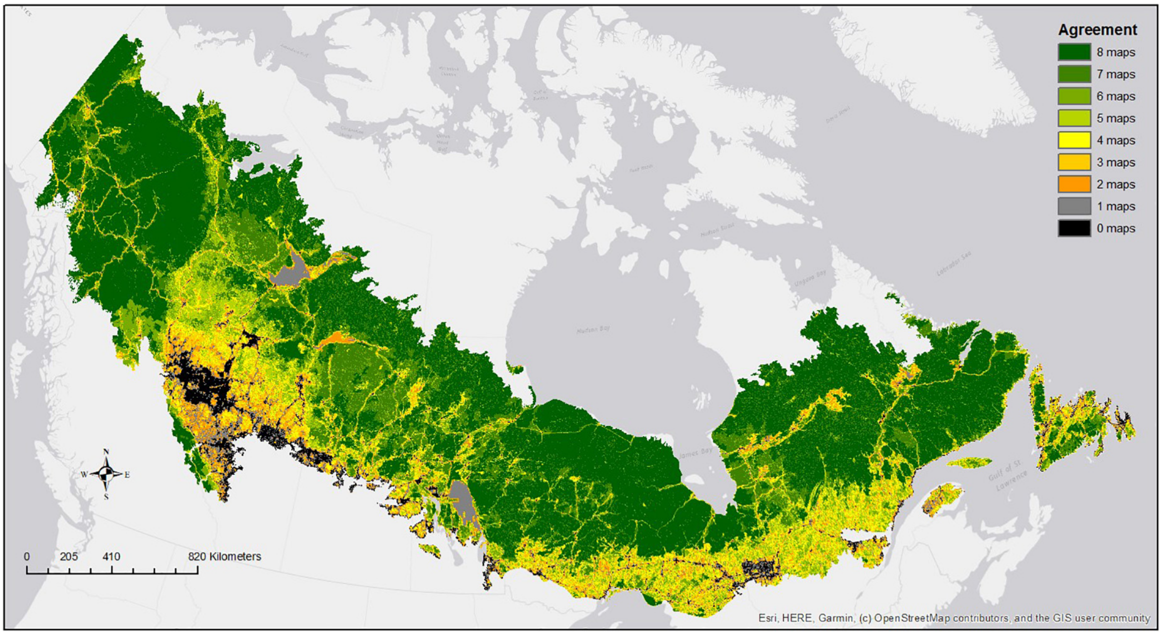

FIGURE 2 | Spatial agreement for intact areas amongst the eight most recent intactness (*N* = 3) and human influence (*N* = 5) maps. Dark green areas indicate areas identified as intact by all datasets. The percent area of agreement amongst 8 maps = 45.1%, among 7 maps = 62.4%, among 6 maps = 70.6%, among 5 maps = 78.5%, among 4 maps = 84.5%, among 3 maps = 89.7%, and among 2 maps = 93.6%. Only 3.6% of the area was identified by only 1 map and 2.8% by no map.

ecosystems in the boreal region. The human influence maps were first reclassified into binary intactness maps to ensure that all maps were comparable. Our results revealed large differences in the area estimated to be intact or relatively free from human influence. In Canada, estimates ranged from 55 to 89% while in Alaska they ranged even more, from 32 to 96%. Likewise, the similarity between pairs of datasets in the Canadian boreal ranged from 0.58 to 0.86 on a scale of 0–1. In total, 45% of the region was identified as intact by the eight most recent datasets. This variation was also evident in the ability of the datasets to account for anthropogenic disturbances that are increasingly common in the boreal region, especially those associated with resource extraction. The five human influence datasets (global and Canadian Human Footprint, Global Human Modification, Large Intact Areas, and Anthromes) omitted 59–85% of all linear disturbances and 28–89% of all polygonal disturbances. In contrast, the Global IFL, Canada IFL, and Human Access maps omitted 2–7% of linear disturbances and 0.1–5% of polygonal disturbances. Several differences in map characteristics, including input datasets and methods used to develop the maps may help explain those differences.

Input datasets appear to play an important role in the variation in intactness estimates, spatial agreement between maps, and the ability to detect both linear and polygonal anthropogenic disturbances. Among the datasets evaluated, the five human influence maps relied mostly on combining existing thematic maps that each represented one stressor into a cumulative disturbance map. The primary stressors used were mostly related to settlement, agriculture, population density and transportation, with little information on resource extraction activities. Exceptions included the use of a forest cover change map (Hansen et al., 2013) by the Low Impact Areas dataset, mining and oil wells by the Global Human Modification dataset, and regional resource extraction datasets by the Canadian Human Footprint. Even so, this did not make a big difference in the omission rates of those disturbances. Moreover, most input datasets were raster maps, or were rasterized (e.g., Williams et al., 2020), with a resolution $\geq$ 1-km^2, which also contributed to the omission of finer-scale anthropogenic changes and disturbances; the Canadian Human Footprint dataset, with a 300-m resolution, was the exception. In contrast, the Human Access and IFL maps mostly relied on processing high resolution satellite imagery (i.e., 30-m) along with some thematic maps to identify disturbances. This resulted in far fewer omissions of anthropogenic disturbances related to resource development such as forest cutblocks, pipelines, seismic lines, and roads. However, the use of even finer resolution test data (i.e., 15-m) revealed increased omission rates, especially for seismic cutlines and roads, whose width make them particularly challenging to detect without imagery of an appropriate resolution. In the case of seismic lines, there has also been a reduction in their width over time which would also contribute to newer lines being undetected by satellite imagery (Lee and Boutin, 2006; van Rensen et al., 2015).

The age and temporal resolution (i.e., how often they are updated) of datasets also has important implications for their suitability for conservation planning, especially in areas of the boreal that are rapidly changing, including the boreal plains

TABLE 5 | Percent length and area omitted (misclassified as intact) by each intactness and reclassified human influence map in the validation study area (boreal caribou ranges).

Disturbance type and amount		HA2010	CIFL2013	GIFL2016	HFP2013	CHFP2019	AB2015	VLIA2015	GHM2016
Intact (%)		**75.3**	**64.9**	**44.9**	**84.2**	**79.7**	**93.4**	**76.2**	**86.8**
	Landsat 30-m resolution—Disturbance type omitted (%)								
Linear disturb	**Length (km)**								
Airstrip	236	3.0	2.1	5.2	42.3	52.7	52.0	59.2	55.3
Dam	34	12.3	12.3	0.0	15.2	30.6	66.0	76.4	69.7
Pipeline	29,925	0.7	0.1	0.0	52.9	78.5	37.0	77.9	51.2
Powerline	14,123	5.0	3.1	0.1	44.7	53.1	71.1	80.0	75.1
Railway	3,191	0.0	0.0	0.0	9.7	0.3	49.2	70.2	67.0
Road	96,559	7.8	3.5	1.6	40.4	47.5	66.0	81.4	65.8
Seismic	161,891	7.4	2.3	3.2	73.5	89.0	61.5	88.9	71.3
Unknown	379	23.9	14.5	33.1	73.7	77.8	88.8	88.4	87.6
Total	*306,338*	*6.7*	*2.5*	*2.2*	*59.0*	*72.3*	*60.9*	*84.8*	*67.7*
Polygonal disturb	**Area (km^2)**								
Agriculture	1,556	0.5	0.0	0.0	2.0	2.9	14.9	17.1	4.7
Cutblock	75,598	4.9	0.7	0.1	56.5	29.1	91.4	56.8	88.1
Mine	812	3.4	0.1	0.1	14.8	16.9	48.5	40.4	31.6
Oil/Gas	167	1.6	0.3	0.0	9.8	14.7	46.2	16.5	9.9
Settlement	851	1.4	0.7	0.3	2.3	4.5	20.7	22.0	9.8
Unknown	117	6.4	3.4	0.4	16.2	23.4	60.8	46.9	36.7
Well site	306	1.9	0.1	0.1	44.4	70.3	72.4	48.3	31.9
Total	*79,407*	*4.7*	*0.7*	*0.1*	*54.2*	*28.3*	*88.5*	*55.3*	*84.6*
	Landsat 15-m resolution—Disturbance type omitted (%)								
Linear disturb	**Length (km)**								
Airstrip	241	3.2	2.3	5.7	42.4	52.8	52.1	59.4	55.6
Dam	36	11.6	11.6	0.0	15.0	29.0	64.9	77.6	69.5
Pipeline	31,621	1.0	0.1	0.1	52.7	78.2	37.0	77.6	51.3
Powerline	14,198	5.0	3.1	0.1	44.7	53.1	71.1	79.9	75.1
Railway	3,247	0.0	0.0	0.0	9.6	0.4	48.7	70.2	66.6
Road	123,945	12.0	6.2	2.5	42.8	49.7	67.4	81.6	66.8
Seismic	272,091	12.3	4.1	3.2	71.5	88.1	60.3	87.8	70.7
Unknown	629	32.1	21.0	28.0	73.0	75.0	86.2	86.6	85.4
Total	*446,008*	*11.1*	*4.4*	*2.7*	*60.9*	*74.9*	*60.9*	*85.0*	*68.4*
Polygonal disturb	**Area (km^2)**								
Agriculture	1,557	0.5	0.0	0.0	2.0	2.9	15.0	17.1	4.7
Cutblock	75,741	4.9	0.7	0.1	56.5	29.1	91.4	56.7	88.0
Mine	815	3.5	0.1	0.1	14.8	16.9	48.6	40.4	31.6
Oil/Gas	170	1.6	0.3	0.0	10.1	15.0	46.7	16.8	9.9
Settlement	858	1.4	0.7	0.3	2.4	4.7	21.0	22.1	10.0
Unknown	127	7.4	3.2	0.4	15.5	22.3	61.4	46.5	35.9
Well site	326	2.2	0.1	0.2	44.4	70.3	72.5	48.6	32.1
Total	*79,594*	*4.7*	*0.7*	*0.1*	*54.2*	*28.3*	*88.5*	*55.3*	*84.5*

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). Older datasets that were only produced once, such as Frontier Forests, may be useful from a historical perspective but would be a poor choice for conservation planning. More recent datasets, such as the Human Access and Canada IFL maps, have now been discontinued leaving only the Global IFL map as a true intactness dataset. The increasingly rapid pace of industrial development means that even recently produced intactness maps

TABLE 6 | Percentage of polygonal (placer mining) and linear (mostly roads) disturbances omitted (misclassified as intact) in the Indian River watershed, Yukon (2,257.4 km^2).

Dataset	Intact area (km^2)	Intact area (%)	Mining (km^2)	Mining omitted (km^2)	Mining omitted (%)	Roads (km)	Roads omitted (km)	Roads omitted (%)
HA2010	1723.7	76.4	64.3	14	21.8	1230.1	467.1	38.0
CIFL2013	1095.0	48.5	64.3	7.7	12.0	1230.1	261.7	21.3
GIFL2016	276.8	12.3	72.2	0.0	0.0	1043.8	19.9	1.9
HFP2013	1245.7	55.2	64.3	2.2	3.4	1230.1	310.3	25.2
CHFP2019	1616.9	71.6	72.2	27.2	37.7	1043.8	508.8	48.7
VLIA2015	2174.8	96.3	72.2	68.7	95.2	1043.8	1023.5	98.1
GHM2016	2168.9	96.1	72.2	47.4	65.6	1043.8	974.9	93.4
AB2015	2064.4	91.5	72.2	56.4	78.1	1043.8	912.9	87.5

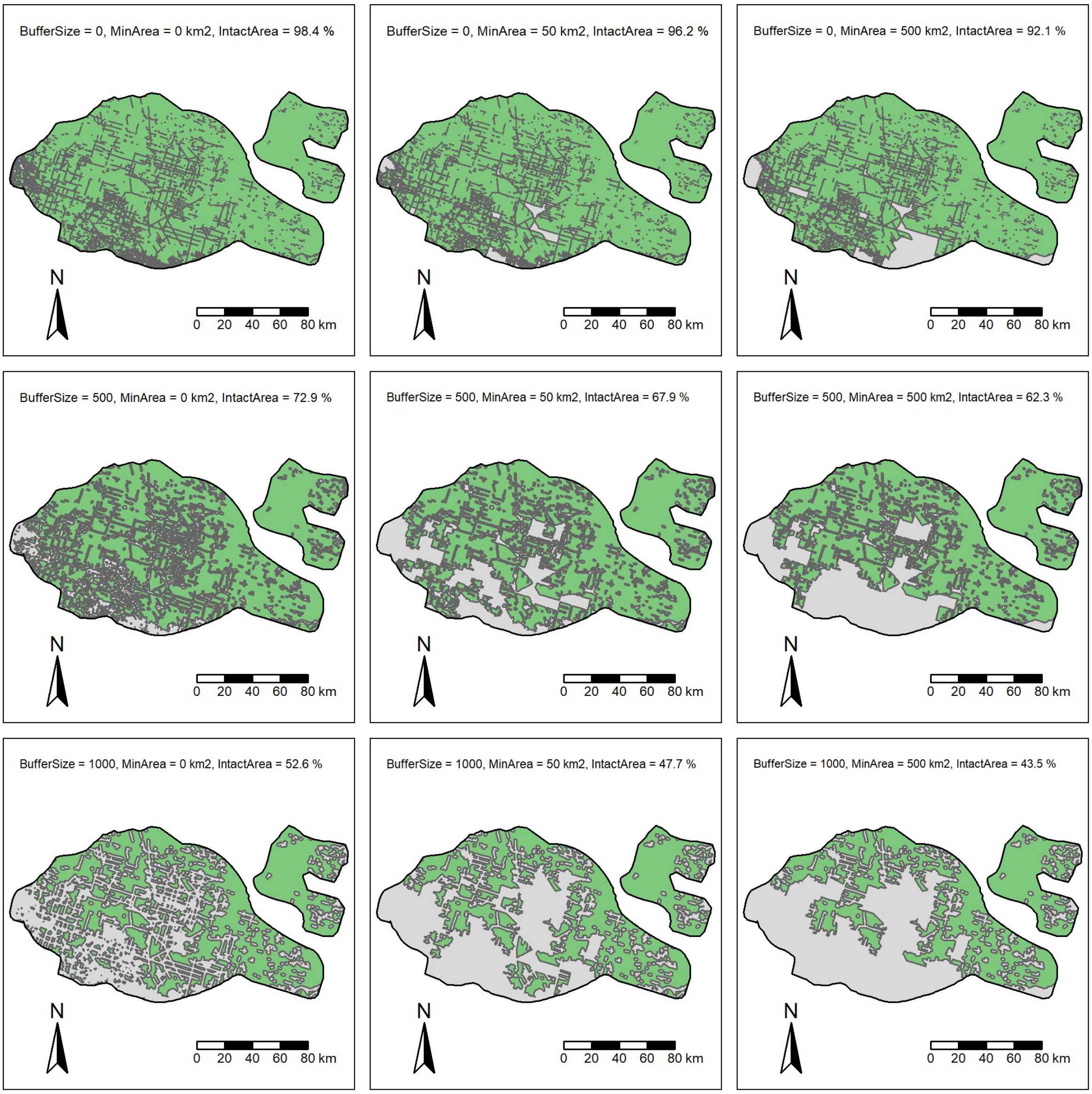

FIGURE 3 | Distribution of intact area identified as a function of buffer size around anthropogenic disturbances and minimum intact patch size.

are quickly out-of-date, highlighting the importance of updating maps on a regular basis, ideally annually. Three datasets, Human Footprint, Anthromes and Global IFL, stood out for having at least three updated products between 2000 and 2016, allowing for monitoring and change detection based on consistent and replicable methods. Newer datasets, such as the Global Human Modification and Low Impact Areas, have only one temporal product but may provide a complementary approach to the Human Footprint for assessing ecosystem conditions at a global scale. In fact, despite their differences, the three multi-year datasets along with the Anthromes datasets provided similar estimates of the amount of remaining terrestrial ecosystems with very low human influence (Riggio et al., 2020). However, despite similar estimates of amount, the location of intact areas differed.

Methodological differences among maps were mostly related to study area delineation, minimum intact patch size, and the use of exclusion buffers around linear and polygonal anthropogenic disturbances. For example, some of the discrepancies between the Frontier Forests and Canada IFL maps are due to the delineation of the Frontier Forests forest zone, which excluded northern, less densely forested portions of the Canadian boreal. Similarly, the Global IFL 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%. The use of a minimum intact patch size also contributed to discrepancies among maps, with four of the maps specifying a minimum size. The Global IFL maps, for example, considered that an intact forest should have a minimum size of 50,000 ha (Potapov et al., 2017). In contrast, the Canada IFL 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 Canada IFL maps. Other maps, such as the Human Access map, did not have a minimum area requirement and consequently identified an even greater amount of intact area. This resulted in higher omission rates for linear and polygonal disturbances in comparison to the IFL maps, especially for areas identified as being intact and smaller than the minimum patch size used by the other maps.

The applied widths of human influence zones (or buffers) also contributed to differences in the extent of mapped intact areas. For example, the Human Footprint 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. In contrast, the more recent Canadian Human Footprint map reduced the influence zone of major rivers to $\leq$ 900 m. 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); impacts of riparian forest harvesting on streams (Richardson and Béraud, 2014)], the use of thresholds eliminated many areas considered intact by the Human Access and IFL 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. Our second case study provided a simple illustration of the sensitivity of IFL estimates to the size of exclusion buffers and the minimum intact patch size on intactness estimates. In particular, the use of buffer exclusion zones by themselves resulted in a much greater reduction in intact areas than the use of a minimum intact patch size criteria on its own. The use of simple buffers around disturbances limits the users' ability to apply 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, 2011), these buffers may be appropriate, and would not represent an underestimation of intact areas. However, when conservation efforts focus on less sensitive species or other values, these buffers may be too conservative and underestimate the amount of suitable area. To be most flexible, intactness mapping projects could avoid using buffers or at least provide underlying unbuffered data.

Overall, and as with input data, the datasets we evaluated can be broadly divided into two groups based on similarities in their methodology, with the IFL and Human Access maps belonging to one group and the four human influence maps belonging to the other. However, even within groups, minor differences in methods resulted in relatively important differences in the areas identified as intact. For example, the Global IFL maps considered all wildfires occurring in proximity to infrastructure (e.g., settlements) as non-intact, resulting in less intact area identified in comparison to the Canada IFL maps (Lee, 2009). Fires play crucial roles in the dynamics of Canadian boreal forests, where most of the area burned is due to lightning-caused fires (Price et al., 2013). This alone would account for an underestimation of 400,000 km^2 of intact boreal and temperate forests in Canada by the Global IFL maps (Lee, 2009). 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 Global IFL maps but not by the Canada IFL and Human Access maps.

Global maps such as the Anthropogenic Biomes, Global Human Modification, Low Impact Areas and Human Footprint maps may be appropriate for broad-scale conservation assessments where finer resolution data are not available. For example, this approach was used to identify and prioritize global wilderness areas (Mittermeier et al., 2003), identify remaining intact areas globally and within biomes (Riggio et al., 2020), and analyze the connectivity of protected areas *via* intact land (Ward et al., 2020). However, obtaining more detailed and up-to-date regional maps of intactness or disturbances should be a priority for any systematic conservation planning exercise, in the boreal or elsewhere. The Canadian Human Footprint map provides such an example, but also reveals the difficulty in acquiring high quality national-scale disturbance data for certain anthropogenic activities such as seismic cutlines. We see a lot of value in expanding and refining high resolution disturbance datasets (e.g., BEAD) to include Alaska and fill in spatial and temporal gaps in Canada, especially given the growing interest in transborder and continental-scale conservation planning initiatives (Beazley et al., 2021). Increasingly, researchers are using freely available satellite imagery (e.g., Landsat 8, Sentinel 2) combined with machine learning approaches (e.g., random forests, deep learning) to produce more current and accurate time series of high resolution land cover maps, including maps that track changes in forest disturbances (White et al., 2017). In addition, there exist several examples of regional intactness and human influence maps in North America and other parts of the world. For example, the Human Footprint approach has been applied at regional scales in the United States and Canada (Leu et al., 2008; Woolmer et al., 2008). Other recent related initiatives have aimed to characterize landscape patterns, forest fragmentation, forest change, and forest landscape integrity at regional (Raiter et al., 2017), national (Wulder et al., 2008; Pasher et al., 2013; Guindon et al., 2014; White et al., 2017) and global scales (Hansen et al., 2013; Grantham et al., 2020). Regional datasets also afford greater sophistication by integrating information on context, connectivity, habitat, and species (Plumptre et al., 2019; Grantham et al., 2020; Mokany et al., 2020). As an indication of the importance of considering intact areas in conservation planning, a major international conference on "Intact Forests in the 21st Century" recently took place in Oxford in 2018[1] to discuss regional and global approaches.

The development of intactness and human influence datasets has also led to some critiques on the utility of the concept of intactness (Innes and Er, 2002; Bernier et al., 2017; Venier et al., 2018) and debates amongst mapping methods (Kennedy et al., 2020; Riggio et al., 2020; Venter et al., 2020). 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. Bernier et al. (2017) reviewed the concept of "primary forest" as a metric of forest environmental quality, and its use by the Food and Agriculture Organization (FAO) for reporting country-level statistics. Of particular concern is the lack of a consistent operational definition resulting in substantial differences in the way primary forest areas are defined and measured within each country, particularly in the context of forests with active natural disturbance regimes. They note that more recent approaches, such as IFLs, provide greater 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. Venier et al. (2018) distinguished between conceptual and operational definitions of an IFL and provide a historical review of the intact forest landscape concept and intactness mapping, both globally and regionally. Both papers point out limitations in the criteria used to map intact areas and argue for a more sophisticated approach, 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. Specifically, the standard operational definition of a Global IFL sets a minimum intact patch size of 50,000 ha, which is arbitrary and disconnected from regional ecosystem processes which may require a smaller or larger minimum size. For example, the minimum intact patch size may be too small for wide ranging species such as caribou and wolverine, and for sustaining ecosystem processes such as wildfires, which can exceed 1,000,000 ha in some parts of the boreal region. Ideally, the minimum size of an intact patch for conservation planning should be related to habitat requirements for focal species and ecological processes (Haddad et al., 2015).

Our analysis has some limitations. For example, we only reviewed existing datasets that were freely available and covered the boreal region of Canada at a minimum, but we did not consider regional datasets. An evaluation of regional intactness and human influence datasets would be useful since many conservation decisions are made at those scales. In addition, our analysis represents a snapshot in time as datasets are continually being produced, revised, or updated, and anthropogenic disturbances are occurring every day in the boreal region. We were also limited in the spatial extent of our accuracy assessment to the Canadian boreal region since we were unable to obtain higher quality disturbance mapping data that covers extensive regions of Alaska. Our evaluation of both intactness and human influence datasets also required that some datasets be reclassified or recoded to binary maps identifying only areas with minimum human impacts. However, not all datasets had a clear "no impact" class, and consequently, we reclassified some of the maps to create an analogous class showing areas with little or no influence. For one dataset, the Global Human Modification map, we used values ranging from 0 to 0.01 to be consistent with methods used by Riggio et al. (2020).

The boreal region of North America is currently undergoing rapid industrial development, and there is an urgent need to quantify changes in ecosystem conditions and to identify new protected areas that complement conservation efforts in working landscapes. Many of these efforts are being led by Indigenous communities, whose rights and title are being eroded by industrial activities and infrastructure, concomitant with increasing recognition of the crucial role their knowledge has played in conserving these highly valued systems (Fletcher et al., 2021). Several datasets have been developed over the last two decades that can be used to assist in assessment, monitoring, conservation planning, and adaptive management. We grouped them into those that combine existing multi-resolution stressor datasets to create a cumulative human influence map and those that use high resolution satellite imagery to identify and map disturbances. For all linear and polygon anthropogenic disturbance types, the former group was shown to be far less effective than the latter at incorporating anthropogenic disturbances related to resource development in the boreal. However, even among the latter group, the use of buffers and minimum patch sizes limit the flexibility of those products to enable more sophisticated conservation planning. Encouragingly, the increasing concern due to climate and land use change is leading to the continued refinement or revision of existing datasets over time and the development of new products using more sophisticated approaches and finer resolution input data. Moreover, many datasets are being provided freely and some with accompanying algorithms and code used to develop them (e.g., the Human Footprint), allowing approaches to be replicated or adapted for regional use. In addition, many Canadian provinces

[1] https://www.eci.ox.ac.uk/if21/

are now making available historical and modern datasets related to resource management and development. Ultimately, the decision on which dataset to use will depend on the objectives of the conservation planning initiative and the availability of the most recent high-quality datasets available in the planning region. Our goal was to contribute to the review and assessment of some widely available datasets and provide some guidance for their use in the boreal context.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PV performed the analyses and drafted the manuscript. SL, SC, KL, AE, MK, and FS contributed to the conceptualization, writing, and editing of the manuscript. All authors approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://github.com/prvernier/intactness

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