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Decline of regional ecological integrity: Loss, distribution and natural heritage value of roadless areas in Ontario, Canada

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ABSTRACT

Only eight years remain to increase nature protection by 20 million ha in Ontario from 10.7% to 30% by 2030 to meet government commitments. Rapid identification and assessment of unprotected roadless areas (RAs) would help to achieve this goal by focussing natural heritage protection efforts in areas with high ecological and conservation value. In Ontario, little is known about the location and extent of RAs, thus the purpose of this study was to map and describe RAs in Ontario, and to discuss their value. Total length of roads in Ontario increased from ~90,000 km in 1916 to ~607,500 km in 2020 – an increase of ~517,500 km (675%) over 104 years. Within Ontario's managed forest region (MFR; excludes the Far North), RAs declined from ~34 million ha in 1916 to ~18.5 million ha in 2020 resulting in a loss of ~15.5 million ha reducing RA cover in the region to 35.6%. Doubling logging production by 2030 per a new Ontario policy could reduce RAs by as much as 20% to ~14.8 million ha by 2030, potentially resulting in their depletion between 2090 and 2100. In 1880, woodland caribou occupied ~43 million ha in Ontario's MFR, which declined to ~10 million ha by 1990. Caribou occupancy in this region could be eliminated by ~2024 and extirpated from all of Ontario by 2070. If all remaining RAs in the MFR were designated as protected areas, Ontario would achieve 92.7% of the 30 × 30 goal. RAs in Ontario continue to be degraded, fragmented and eliminated.

1. Introduction

Protection of the world's remaining roadless areas (RAs) from further human encroachment, particularly those that are forested, may currently be the most effective and efficient terrestrial nature-based solution to decelerate the biodiversity-climate crisis and to maintain ecological integrity at local to global scales (Ibisch et al., 2016; Psaralexi et al., 2017; Woodley et al., 2021; Tisler et al., 2022). Forest conservation strategies, including protecting primary (unlogged) forests, offer the highest potential of all terrestrial nature-based climate solutions in Canada between now and 2050 (Drever et al., 2021). For example, protection of old-growth forests in British Columbia, Quebec, and Alberta was estimated to sequester and store ~4 Tg CO_2e/yr. in the year 2030, ~15 Tg CO_2e/yr. from 2031 to 2050, and cumulatively ~235 Tg CO_2e by the year 2050 (Drever et al., 2021), which is roughly a third of Canada's annual anthropogenic production of CO_2. Beyond climate mitigation, natural climate solutions have the added benefit of providing habitat for wildlife (Pouteau et al., 2022), and for provision of ecosystem services such as flood mitigation, air and water purification, and pollination for human benefit.

Whether the goal is to protect pristine RAs or to restore a severely degraded landscape, Woodley et al. (2021) state that the preferred conservation solution is the creation of functional ecological networks to provide landscape connectivity that prevents habitat fragmentation and that decelerates climate warming through carbon sequestration and storage. One unique advantage of ecological networks are their emergent properties (the whole is greater than the sum of its parts) derived from numerous small reserves acting together (e.g., migration routes, gene flow, etc.), that only a few large protected areas possess. Functional ecological networks are most effectively achieved through the establishment of wildlife corridors that provide as much high-quality habitat as possible, or areas set aside for restoration, connecting isolated and often degraded parks and reserves (Hilty et al., 2020).

Today and into the future, perhaps the most important value of wildlife corridors is provision of habitat to the many species currently undergoing habitat modifications and range shifts due to climate warming (e.g., Wallingford et al. 2020). For many jurisdictions striving to increase their inventory of parks, reserves, and conservation corridors (Woodley et al., 2019; CPAWS, 2021), the sites with highest native

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biodiversity, ecological integrity, and landscape resiliency are RAs by virtue of the absence of intensive human activities including road construction and use (Selva et al., 2015; Ibisch et al., 2016; Watson et al., 2016; Psaralexi et al., 2017; Tisler et al., 2022). Legislation defining the selection and management of parks and reserves in Ontario is driven at the highest level by the concept of ecological integrity (Province of Ontario, 2021), which is the focus of most park management agencies – *to maintain and restore the ecological integrity of protected lands and waters* (Wurtzebach and Schultz, 2016; McMullin et al., 2017).

More than two decades ago, RA assessment and monitoring was proposed as the foundation of a *State-of-the-Wilderness* reporting system for Ontario (Davidson et al., 1999) designed to, "*…address the need to protect, restore and monitor wilderness*" and to "*…help develop, market and manage a wilderness-based ecotourism industry*." However, this system was never instituted, rather a *State of Ontario's Protected Areas* reporting system (e.g., OMECP 2021) was developed and applied without including RAs as a landscape-level metric for assessment or monitoring.

Rapid identification and description of unprotected RAs would provide immense benefits by focussing natural heritage protection efforts in areas with the highest native biodiversity, ecological integrity, and landscape resiliency (Davidson et al., 1999; Center for Biological Diversity, 2021; Sierra Forest Legacy, 2021). Only eight years remain to increase nature protection in Ontario from 10.7% to 30% by 2030 as directed by the Federal Government of Canada (CPAWS, 2021) This 30 × 30 strategy provides benefits that outweigh costs by a ratio of at least 5-to-1 (Waldon et al., 2020). For Ontario, this will require the addition of roughly 20 million ha to the Ontario Protected Areas System, which scales to a rate of 2.5 million ha/yr.

Rather than develop a specific strategy to increase land protection to meet the 30 × 30 goal, however, the Ontario government has adopted a forest harvesting strategy that is designed to double logging by 2030 (OMNDMNRF, 2021a). By increasing soil disturbance and the rate of forest biomass removal primarily from pristine, unlogged landscapes, this logging increase will significantly accelerate both biodiversity loss and climate warming provincially, nationally, and globally. In addition, despite recent evidence showing that the managed (logged) forest region (MFR) of Ontario is now a source of atmospheric carbon (ECCC, 2021; Saxafrage, 2021), they continue to be treated as a carbon sink by current provincial and federal climate warming mitigation policies (Skeen, 2021).

However, through the Woodland Caribou Conservation Plan (OMECP, 2022), the Ontario government has committed to managing for "self-sustaining populations [of caribou] in a healthy boreal forest" by (1) maintaining genetically-connected local populations of woodland caribou where they currently exist, (2) improving connections and security among isolated populations, and (3) facilitating the return of caribou to strategic areas. If successful, these strategies may also result in the protection of additional roadless areas.

RAs and their ecological value are rapidly declining world-wide, and identifying their location and extent is a global as well as a Canadian conservation imperative (Poley et al., 2022). Currently in Ontario, RA location and extent are poorly understood. Thus, the purpose of this study was to produce a map of RAs in Ontario using regional-scale roads data (most complete), to describe basic features and the decline of RAs, to address causes for these declines, and to discuss the future of RAs in Ontario particularly in the context of expanding the provincial protected areas system. We include two case studies; one that examines the decline of an at-risk, disturbance-sensitive large mammal – woodland caribou (*Rangifer tarandus caribou*) in Ontario, and one that compares landscape composition between RAs and the human matrix (HM; areas outside of RAs) in the Bancroft-Minden Forest Management Unit (BMFMU) located in south-central Ontario. This forest management unit was chosen based on our relatively high familiarity with it.

2. Methods

2.1. Provincial-level analyses

Data were obtained from the Ontario Road Network (ORN) and Ministry of Natural Resources and Forestry (MNRF) road segment datasets available from Land Information Ontario (LIO) through their *GeoHub* website (Table 1). Data were downloaded from this website directly or received from LIO staff when a data request was submitted as ArcGIS geodatabase files and shapefiles. Additional data describing permanent and logging roads inside Algonquin Provincial Park were obtained from the Algonquin Forestry Authority, the Wilderness Committee, and Ancient Forest Exploration & Research. To estimate the rate of loss of RAs in Ontario since 2005, we compared buffered (1 km) digital road networks (primary, secondary, tertiary) from 2005 to 2020. A combination of ArcMap (10.8.0) and QGIS (3.10) were used to perform GIS processing on the shapefiles.

RAs were defined as any area in the province, except the Great Lakes, that were at least 1 km from a road or logged area (contains skidder roads and trails) as defined by the datasets in Table 1. This is not to be confused with an *intact forest landscape*, which also excludes areas disturbed by logging but has a minimum size of 50,000 ha (Potapov et al., 2017). For our study, RAs as small as 1 ha were included given the paucity of RAs of any size in southern Ontario – only 0.3% of RAs in Ontario are larger than 50,000 ha. By using an expanded buffer to include all known human disturbances as well as roads, our RAs also differed from those defined by Ibisch et al. (2016) and Poley et al. (2022) who only buffered from roads.

Our approach, also used by Davidson et al. (1999) for their Ontario RA study, was applied in order to identify only the *pristine* roadless areas given their greater ecological-conservation value compared to disturbed RAs. Only 0.43% of the known logged area in Ontario (from 2007 FRI) was located outside of the 1 km road buffer, which makes comparisons with results from Ibisch (2016) not perfect but viable, particularly at the regional-provincial scale of millions of ha.

Roads were defined as linear features including road segments and railway track lines. Each road (ORN and MNRF road segments), and railway shapefile was buffered by 1 km and were merged into one shapefile. Archived LIO Ontario Base Mapping (OBM) from 2005 was used to create a road segment file and an RA dataset for that year in the entire Province of Ontario.

Forest Resource Inventory (FRI; 2007) data were used to identify forest stands that had been previously logged. Roads and logged areas were buffered by 1 km and all areas outside of buffers made up the RAs. The year 1890 was selected as the earliest data point for RA area in Ontario's managed (logged) forest region (MFR; 53 million ha) since that was roughly when automobiles became a commonly used vehicle on roads throughout the province. We doubled the amount of RA loss in 2020 to estimate the amount remaining in 2030 to account for the projected increase of timber production in the province.

Projections and coordinates: Coordinate System: NAD_1983_Ontario_MNR_Lambert; Projection: Lambert_Conformal_Conic; False_Easting: 930000.00000000; False_Northing: 6430000.00000000; Central_Meridian: -85.00000000; Standard_Parallel_1: 44.50000000; Standard_Parallel_2: 53.50000000; Latitude Of Origin: 0.00000000; Linear Unit: Meter.

2.2. Case study analyses

In the Province of Ontario, industrial logging practices, defined by the *Crown Forest Sustainability Act* (1994), are restricted to the Area of the Undertaking (AOU) where private companies bid for "sustainable forest licenses – SFLs" that permit road-building, logging operations, and other forest management activities on public lands within estab-

Table 1
Table 1 - Data Sources.

Table 1 – Data Sources (part a)

DATA TYPE	DATABASE NAME	DATE	SOURCE
Road Network	Ontario Road Network (ORN) Segment With Address	2020	https://geohub.lio.gov.on.ca/datasets/mnrf::ontario-road-network-orn-road-net-element
	MNRF Road Segments	2020	https://geohub.lio.gov.on.ca/datasets/mnrf-road-segments?geometry=-158.829%2C38.917%2C-10.645%2C58.786
	Algonquin Park logging road (includes main roads)	2020	Wilderness Committee and Algonquin Forestry Authority (WC-AFA)
	Algonquin Park logging road (includes main roads)	2020	volunteer GIS specialist
	26 Road segment files (one for each MNRF district)	2005	https://imageryorders.exavault.com/share/view/2ary2-b35lsgsd-ekecll7j
Utility Lines	Utility Line		https://geohub.lio.gov.on.ca/datasets/mnrf::utility-line?geometry=-158.829%2C38.917%2C-10.645%2C58.786
Railways	Ontario Railway Network (ORWN)		https://geohub.lio.gov.on.ca/datasets/mnrf::ontario-railway-network-orwn
Provincial Boundary	Province		https://geohub.lio.gov.on.ca/datasets/province?geometry=-158.829%2C38.917%2C-10.645%2C58.786
Harvested Forest Stands	Forest Resources Inventory Packaged Products - V1		https://geohub.lio.gov.on.ca/datasets/forest-resources-inventory-packaged-products-version-1
	Forest Resources Inventory Packaged Products - V2		https://geohub.lio.gov.on.ca/datasets/forest-resources-inventory-packaged-products-version-2
Crown Land	Crown land: ministry unpatented land		https://geohub.lio.gov.on.ca/datasets/crown-land-ministry-unpatented-land
Site District	Site District		https://geohub.lio.gov.on.ca/datasets/site-district
Site Region	Site Region		https://geohub.lio.gov.on.ca/datasets/site-region-?geometry=-158.829%2C38.917%2C-10.645%2C58.786
Table 1 – Data Sources (part b)			
100K Waterbodies	Ontario Hydrographic Network		https://geohub.lio.gov.on.ca/datasets/mnrf::ontario-hydro-network-ohn-waterbody
Protected Areas	Areas of Natural and Scientific Interest (ANSI)		https://geohub.lio.gov.on.ca/datasets/areas-of-natural-and-scientific-interest-ansi
	Conservation Reserve Regulated		https://geohub.lio.gov.on.ca/datasets/conservation-reserve-regulated
	Crown Game Preserves		https://geohub.lio.gov.on.ca/datasets/crown-game-preserves
	Federal Land Other		https://geohub.lio.gov.on.ca/datasets/federal-land-other
	Federal Protected Land		https://geohub.lio.gov.on.ca/datasets/federal-protected-areas
	Indian Reserve		https://geohub.lio.gov.on.ca/datasets/indian-reserve
	Municipal Park		https://geohub.lio.gov.on.ca/datasets/municipal-park
	National Wildlife Area		https://geohub.lio.gov.on.ca/datasets/national-wildlife-area
	NGO Nature Reserve		https://geohub.lio.gov.on.ca/datasets/ngo-nature-reserve
	Natural Heritage System Area		https://geohub.lio.gov.on.ca/datasets/natural-heritage-system-area
	Provincial Park Regulated		https://geohub.lio.gov.on.ca/datasets/provincial-park-regulated
Algonquin Park Zones	Algonquin Park Zoning (incl protection status)		by request only from geohub.lio.gov.on.ca

lished forest management units. Due to a familiarity with the region, our case study comparing RAs to the HM focussed on the BMFMU, located within the southern region of the AOU comprising ~991,400 ha. Historical caribou occupancy area (ha) data were obtained from the map provided by Cummins and Beange (1993) showing the recession of caribou range in Ontario with occupancy boundaries shown for 1880, 1900, 1950 and 1990.

To compare RAs to the HM, we used ArcMap (10.8.1) GIS software and data from Ontario GeoHub. Roads, logged areas, and settlements were buffered by 1 km and included in the HM. Roads data were obtained from the Ontario Road Network and the Ministry of Natural Resources and Forestry (MNRF) Road Network, railways data came from the Ontario Railway Network, and other linear features were obtained from the Ontario Utility Line dataset. All areas not included within the HM were defined as RAs. Forest Resource Inventory (FRI, 2007) data were used (1) to identify forest stands that had been previously logged, (2) to examine differences in land cover types between the RAs and the HM, (3) to examine differences in forest dominance types between the RAs and the HM, (4) to assess for gains and losses of forest dominance types in the HM through comparison with the 1987 FRI data, and (5) to compare old-growth features between the RAs and the HM.

Land type classification statistics were calculated from the intersection of the 2007 FRI with both the RA and HM polygons. For each intersection, the areas that made up each of the ten land type classes were summed and a percentage was calculated. The abundances of the 2007 FRI 'lead species' metric for both RAs and the HM were compared to determine differences of forest composition between them. The change over time analysis (20 yrs.) compared the 'working group' metric in the 1987 dataset (start time) to the lead species metric in the 2007 FRI dataset (end time) to determine if the area occupied by each forest dominance type either increased or decreased and by how much over the 20-year period.

Old-growth forest metrics included total area, mean age, site quality and mean stand size. Stand age within the 2007 FRI dataset was adjusted to reflect stand age in 2021 (+14 yrs.). Based on stand age and the tree composition of the overstory lead species, old-growth stands were identified by excluding stands younger than the "age of onset" (minimum age) specified in OMNRF (2003), and stands with previous logging activity (from 2007 FRI; since 1988), and by summing the area of each lead species stand type for RAs and for the HM.

3. Results

3.1. Provincial level

3.1.1. Decline of RAs and caribou in Ontario's managed forests

Total length of roads in Ontario increased from ~90,000 km in 1916 to ~607,500 km in 2020 – an increase of ~517,500 km (675%) over 104

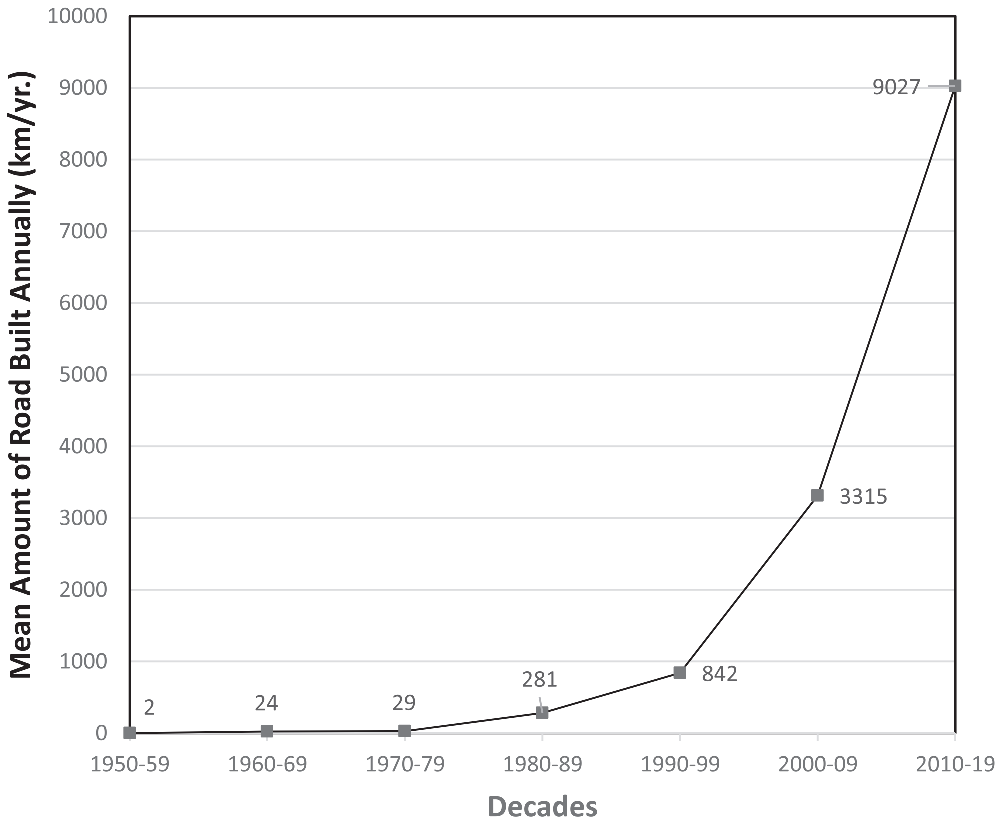

Fig. 1. Resource roads expansion in Ontario, 1950–2019.

years for a mean rate of ~5000 km/yr. However, road expansion has not been increasing in linear fashion as shown by the exponential increase of resource (tertiary) roads in Ontario from 1950 to 2019 (Fig. 1). Within Ontario's managed forest region (MFR), including only the AOU and southern Ontario, the construction and use of new roads and associated logging activity contributed to a decline in RAs from ~34 million ha in 1916 to ~21 million ha in 2005, a mean rate of loss of ~146,000 ha/yr. (Fig. 2). Between 2005 and 2020, the rate of RA loss increased by about 41,000 ha/yr. to a mean of 187,175 ha/yr. resulting in a loss of ~2.8 million ha of RA over the 15-year period in the MFR. Considering the potential effects of a recent government policy to double logging production by 2030 (OMNDMNRF, 2021a), RA amount in Ontario could be reduced by as much as 20% to ~14.8 million ha by 2030 (Fig. 2). Based on historical mapping (Cumming and Beange, 1993), we estimated that in 1880, woodland caribou (*threatened species*) occupied ~43 million ha in Ontario's MFR, which declined to ~39 million ha in 1900, to ~22 million ha in 1950, and to ~10 million ha in 1990 (Fig. 2). During this time, RAs in Ontario's MFR also declined reaching ~18.5 million ha in 2020 (Fig. 2). The similar slopes of these two curves indicate similar rates of decline.

3.1.2. *Spatial patterns*

The roughly 54 million ha of RAs in Ontario were distributed as follows: southern Ontario – 0.2% (91,668 ha), AOU – 34.1% (18,440,436 ha), and the Far North – 65.7% (35,505,490 ha), totalling to 60.6% of the province (Table 2). RAs are largest and most abundant in the Far North and become smaller and less frequent with progression to the most southern portions of the province (Fig. 3). Southern Ontario, the smallest at 9.2% of the province, had the highest road density at 27.5 km/1000 ha, had the lowest natural heritage protection at 1.3%, and had 91,668 ha of RAs with 14.2% (13,015 ha) of RAs protected (Table 2). At the opposite extreme, the Far North (41.6% of the province), was characterized by an extremely low road density (0.2 km/1000 ha), had 9.8% natural heritage protection, and was almost completely composed of RAs at 95.6% (~35.5 million ha). However, only about 10% of Far North RAs were protected. The Area of the Undertaking (AOU), the region of industrial logging defined by the *Crown Forest Sustainability Act* (Province of Ontario, 1994), was the largest of the three regions occupying 49.1% of the province. Road density there was intermediate between the other two regions at 8.6 km/1000 ha, natural heritage protection (11.2%) was highest, and 42.1% of the region (~18.4 million ha) was composed of RAs with almost 22% or 4 million ha of them protected.

3.1.3. *Size classes*

For the entire province, there were 210 RAs larger than 10,000 ha, which was the minimum "self-sustaining" RA size (maintains regional native biodiversity and ecological integrity) used by Ibisch (2016), and 50 RAs larger than 50,000 ha, the minimum self-sustaining RA (or *intact forest landscape*) size used by GFW (2021) (Table 3). In southern Ontario, 54.7% of RAs were smaller than 10 ha, 83.7% were smaller than 100 ha, and 98.7% were smaller than 1000 ha. None of the RAs in this region were larger than 10,000 ha. In contrast, 62.7% of RAs in the Far North were larger than 1000 ha with 20 RAs larger than 10,000 ha and 12 RAs larger than 50,000 ha. In the AOU, 52% of RAs were smaller than 10 ha, 76% were smaller than 100 ha, and 93% were smaller than 1000 ha. However, 190 RAs in this region (1.3%) were larger than 10,000 ha and 38 (0.3%) were larger than 50,000 ha.

3.2. *RAs in the bancroft minden forest management unit*

3.2.1. *Land type differences*

Rock and wetlands in the BMFMU (Fig. 4) were much more abundant in RAs whereas human infrastructure, agriculture, and grass-meadow, were much more abundant in the HM (Table 4). Wetlands (open and treed) make up almost 10% of the total RA area within the BMFMU, which is double the amount of wetland cover in the HM (5% cover). Rock occupies almost 8% of the RA area, which is about ten times higher than the relative abundance of rock in the HM (0.8%). Productive forest

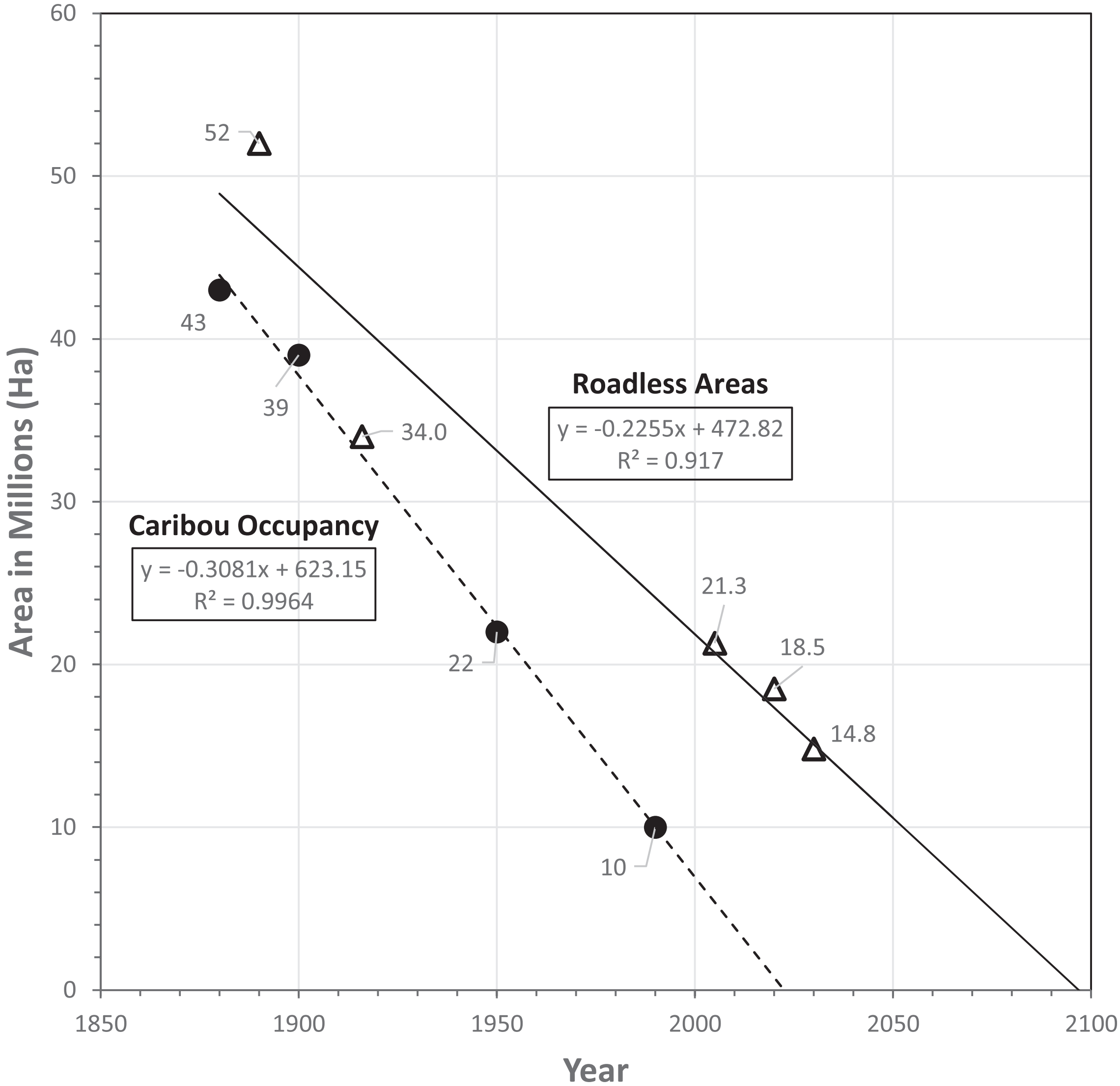

Fig. 2. Long-term decline of roadless areas and caribou occupancy in Ontario's Managed Forests, 1880–2030 (caribou data from Cumming and Beange (1993); 1916 roads data from OMT (2021)).

was by far the most abundant land type within the BMFMU at 75.2% in the HM and was 5% lower in the RAs at 70.2%. The cover of water was also slightly higher in the HM (9.9%) compared to RAs (8.7%).

3.2.2. Forest dominance type differences

For those forest dominance types with at least 2% relative abundance, red oak, white pine, poplar, and red maple were more abundant in RAs with factor differences of 3.3, 3.0, 1.4, and 1.2, respectively, compared to the HM (Table 5). Those forest types that were more abundant in the HM included those dominated by white birch, balsam fir, and sugar maple with factor differences of 3.3, 2.8, and 2.2, respectively compared to RAs.

3.2.3. Forest type declines

Five late-successional forest dominance types declined in the HM portion of the BMFMU between 1987 and 2007 (Table 6). Three of these forest types declined precipitously including American beech forest (82%), larch forest (70%), and white cedar forest (57%), and two declined less severely including sugar maple forest (13%) and eastern hemlock forest (12%). The greatest area loss occurred with sugar maple declining from 285,684 ha in 1987 to 248,556 ha in 2007 for an mean rate of decline of 1856 ha/yr. totalling to a loss of 37,128 ha over 20 yrs. White cedar forest also declined significantly from 52,506 ha in 1987 to 22,656 ha in 2007 for a mean rate of decline of 1492 ha/yr. totalling to a loss of 29,850 ha over the 20 yr. period.

3.2.4. Old-growth forests

The relative amount of old-growth forest was 1.2 times higher in the RAs of the BMFMU compared with the HM (Table 7). In addition, mean old-growth forest age was higher in RAs, however, only by 2 yrs. Mean site quality was slightly higher (1.15x) and mean stand size was 1.5 times higher for old-growth forests in the HM compared to RAs.

4. Discussion

4.1. Road development in Ontario

The publication, *The Ministry of Transportation 1916-2016: A History* (OMT, 2021), served as the primary source of information for this subsection. In 1793, the first permanent road built in Ontario stretched eight miles from Kingston to Bath. Three years later, Yonge Street from Toronto to Lake Simcoe was constructed by the British military. These and other roads of this time period were often only usable during dry weather or when frozen. It was not until the early 1800s, that the gov-

Table 2
Landscape metrics for roadless areas in three broad regions of Ontario, 2020 (excluding lakes).

Landscape Metric		Regions Far North	Area of the Undertaking (AOU)	Southern Ontario	All Regions (entire province)
Total Area	Ha	37,146,382	43,827,853	8,230,610	89,204,845
	%	41.7	49.1	9.2	100.0
All Roads (primary, secondary & tertiary)	Length (Km)	5563	375,582	226,416	607,561
	% of Province	0.9	61.8	37.3	100.0
	Density (Km/1000 Ha)	0.2	8.6	27.5	6.8
Area Protected	Ha	3,654,728	4,923,880	109,325	8,687,933
	% of Region	9.8	11.2	1.3	9.7
Roadless Areas	Ha	35,505,490	18,440,436	91,668	54,037,594
	% of Region	95.6	42.1	1.1	60.6
Roadless Areas Protected	Ha	3,498,582	4,043,243	13,015	7,554,840
	% of Region RA	9.9	21.9	14.2	14.0
	% of Region	9.4	9.2	0.2	8.5

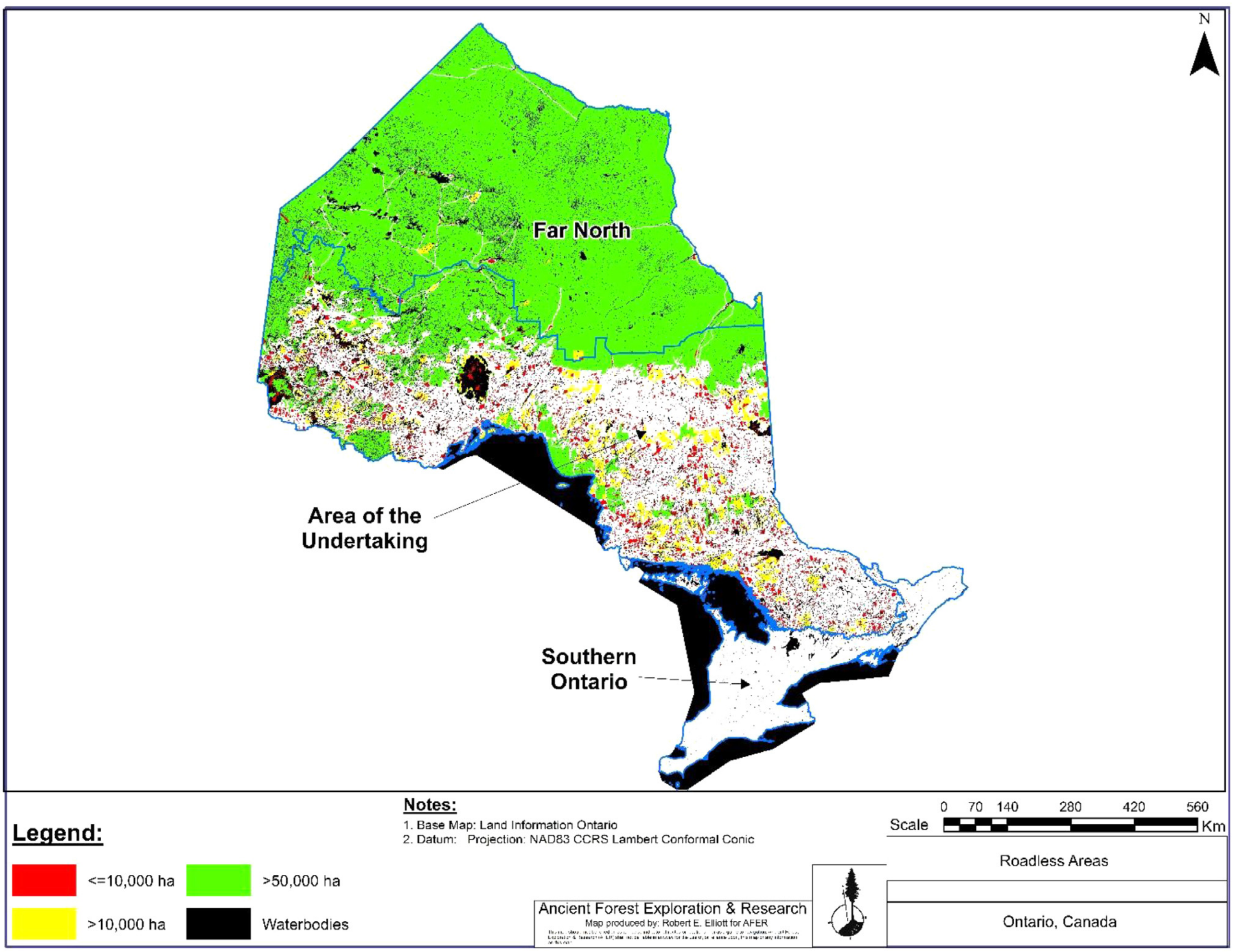

Fig. 3. Roadless areas in Ontario (without lakes).

ernment became more involved in building and maintaining roads in order to facilitate government administration, movement of the military, foster commerce, improve the postal service, and to open new areas for settlement. Due to government incompetence during the latter half of the 1800s, Ontario roads were in serious disrepair, however, with the advent of the automobile, this began to change in the 1890s.

In 1916, the Department of Public Highways of Ontario was established. At that time, there were 50,000 km of gravel road as well as 40,000 km of macadamized dirt roads throughout the province. During the 1920's, 15,560 km of county roads and 2920 km of provincial highways were constructed. By 1937, roads managed by the Department of Northern Development were merged with the provincial road system adding 13,000 km of county roads. Many of these early roads facilitated access to and removal of timber representing a transition away from the use of waterways to transport logs to market. This new mode of transporting logs, along with other operational improvements, significantly increased the amount of timber harvested in the province while employing ever fewer people. For example, from the 1960s to the 1990s, the average annual area logged in the AOU increased by over 50% and the number of people employed in the industry decreased by roughly the

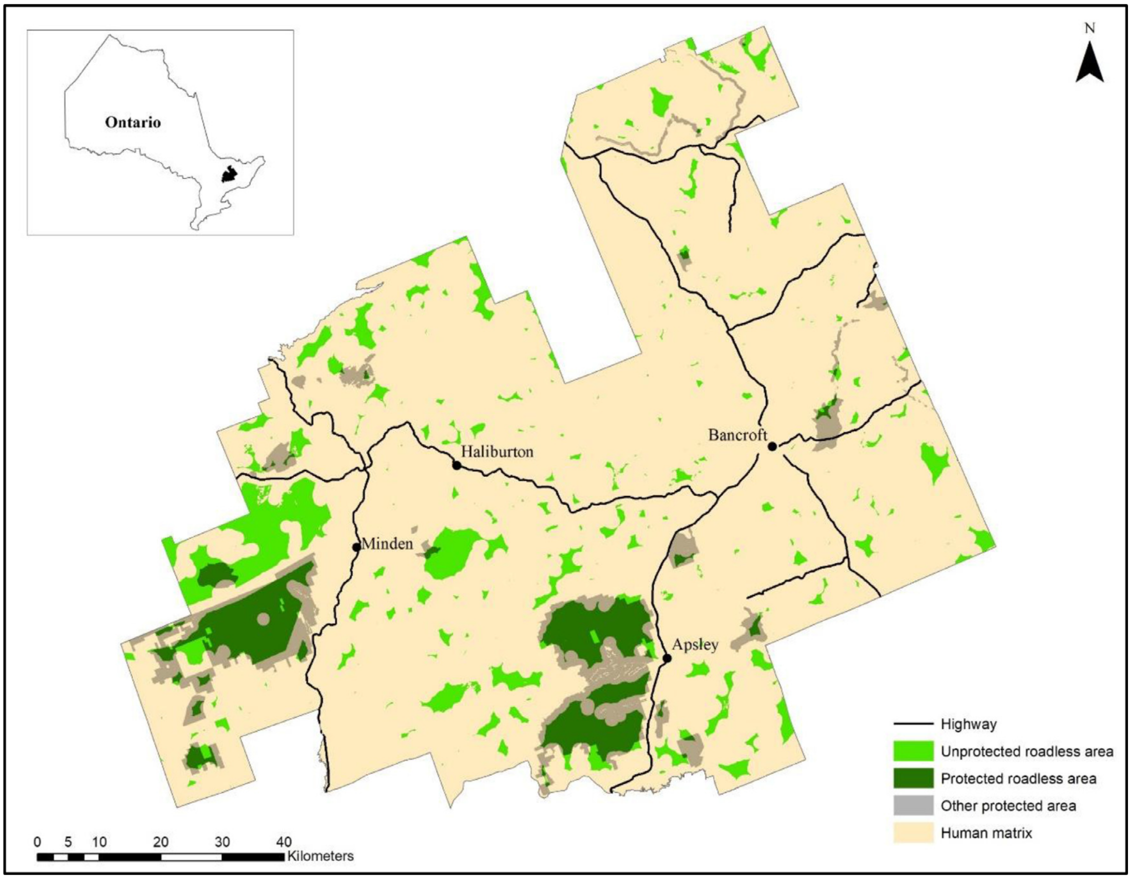

Fig. 4. Bancroft minden forest management unit, Central Ontario.

same amount (LCO, 2012). Accessing pristine forested areas to log required the construction of many new roads over this time period (e.g., Fig. 1) and by 2005, there were ~505,000 km of roads in Ontario that increased to ~607,500 km in 2020.

4.2. Roadless areas research in Canada

Although the concept of RAs has been around for almost a century (Leopold, 1925), very little work has been done in Canada to identify, map and assess the rate of decline of RAs. More than 25 years ago, Rutledge and Vold (1995) found that 13 million ha of RA were lost in British Columbia from 1994 to 2014, representing a decline of 650,000 ha/yr. – a rate more than three times higher than for Ontario between 2005 and 2020 (187,175 ha/yr.). Assuming that this loss in British Columbia represented 20% of the RA loss in Canada, they further estimated that during this time, 3.25 million ha/yr. of RA were lost throughout Canada. This was considered to be a conservative estimate since it did not include roads associated with oil, natural gas and mining development. The only provincial government in Canada that has produced publicly-available, user-friendly RA mapping is British Columbia (Province of British Columbia, 2021). However, since they used a road buffer of 500 m, their RA mapping cannot be compared with ours, which used a 1 km buffer. Although Davidson et al. (1999) provided a map of RAs in Ontario, the low resolution, small scale, and the non-digital format make it unusable. Recently, Poley et al. (2022) found that regional-scale roads datasets are far superior to available national and global roads data for assessing and describing roadless areas in Canada.

4.3. Decline of RAs and woodland caribou

The construction and use of ~600,000 km of roads within Ontario's MFR were and continue to be the primary causes of RA decline (Jackson et al., 2000; Bowman et al., 2010; Drever et al., 2010; Boan et al., 2018; Coffin et al., 2021). At the current rate of loss, we estimate that RAs in Ontario's MFR could become depleted sometime between 2090 and 2100 (Fig. 2). In 1880, woodland caribou occupied

Table 3
Frequency of roadless areas by size class in three broad regions of Ontario (excluding lakes).

Region	Frequency of Roadless Areas by Size Class 1-10 (Ha)	11-100 (Ha)	101-1000 (Ha)	1001-10,000(Ha)	10,001-50,000(Ha)	>50001(Ha)	Total (Ha)
S. Ontario	575	305	158	14	0	0	1052
	(54.7%)	(29.0%)	(15.0%)	(1.3%)	(0%)	(0%)	(100%)
AOU	7430	3507	2439	827	152	38	14,393
	(52.0%)	(24.0%)	(17.0%)	(5.7%)	(1.0%)	(.3%)	(100%)
Far North	9	3	8	14	8	12	54
	(17.0%)	(5.5%)	(14.8%)	(25.9%)	(14.8%)	(22.0%)	(100%)
All Regions	8014	3815	2605	855	160	50	15,499
	(51.7%)	(24.6%)	(16.8%)	(5.5%)	(1.0%)	(0.3%)	(100%)

Table 4
Land Type Composition Differences between Roadless Areas and the Human Matrix in the Bancroft Minden Forest Management Unit, Ontario (RA = roadless area; HM = human matrix; Factor Difference = larger value/smaller value).

Land Type	RA (%)	HM (%)	Factor Difference
Rock	7.9	0.8	9.9
Open Wetland	9.0	4.6	2.0
Treed Wetland	0.6	0.3	2.0
Islands	0.2	0.1	2.0
Brush and Alder	2.2	1.3	1.7
Productive Forest	70.2	75.2	1.1
Water	8.7	9.9	1.1
Grass and Meadow	1.3	2.6	2.1
Agriculture	0.1	1.1	11.4
Human Infrastructure	0.1	4.1	40.5

Table 5
Comparing the Relative Abundance of Forest Dominance Types between Roadless Areas and the Human Matrix in the Bancroft Minden Forest Management Unit (RA = roadless area; HM = human matrix; Factor Difference = larger value/smaller value).

Forest Dominance Types	RA %	HM %	Factor Difference
Red Oak	20.4	6.2	3.3
White Pine	13.3	4.4	3.0
Poplar	19.6	17.2	1.4
Red Maple	15.0	12.5	1.2
Sugar Maple	17.7	38.2	2.2
Balsam Fir	1.3	3.7	2.8
White Birch	1.0	3.3	3.3

Table 7
Comparison of old-growth forest metrics between roadless areas and the human matrix in the bancroft minden forest management unit (RA = roadless area; HM = human matrix; Factor Difference = larger value/smaller value).

Old-growth Forest Metrics	RAs	HM	Factor Difference
Percent of Total Area	17.0	14.2	1.20
Mean Age (yrs)	119	117	1.02
Mean Site Quality	0.67	.77	1.15
Mean Stand Size (ha)	9.3	13.9	1.49

~43 million ha in Ontario's MFR, which declined to ~10 million ha in 1990 (Fig. 2). Based on these trends, caribou occupancy in the MFR could be eliminated by ~2024. Masood et al. (2017) predict the extirpation of woodland caribou throughout all of Ontario by 2070 – less than 50 years from now – due to both habitat loss and climate warming.

While our data show strong evidence of a linear trend, it is likely that both curves will show asymptotic behaviour over time as amounts (ha) remaining approach zero. Our extrapolations may not prove accurate, particularly since the Ontario Woodland Caribou Conservation Plan calls for the maintenance and restoration of caribou habitat. However, both linear regressions clearly show a rapid decrease in both caribou occupancy and RAs, and the similarity of the slopes indicates some degree of correlation.

It is very unlikely that caribou will reach zero occupancy by 2024 since throughout northern portions of the AOU, small numbers of caribou still utilize scattered habitat patches (Wilson et al., 2019). This northern AOU boundary is contiguous to the most southern portions of the Far North region and closely matches the 1990 southern caribou range limit boundary (Cumming and Beange, 1993; Schaefer, 2003). Due to numerous factors that interact to depress caribou numbers there, however, these higher quality occupancy patches compose only about 50% of this east-west boundary area (Wilson et al., 2019). Negative factors include anthropogenic disturbances (roads, forestry, mining), competitors including moose and deer, and predators including mainly wolves, all of which are under the dynamic and continuing influence of climate warming (Masood et al., 2017; Wilson et al., 2019).

4.4. Global and regional context

4.4.1. Global

In 2016, roughly 80% of the Earth's terrestrial surface was roadless and 7% of the Earth's RAs were larger than 10,000 ha (Ibisch et al., 2016). In contrast, RAs in Ontario in 2020 made up about 61% of the province, which is 19% lower than the global mean in 2016. In addition, the percentage of RAs greater than 10,000 ha in Ontario (1%) was 6% lower than the 2016 global mean of 7%. The general spatial patterns of RA density and size for Ontario as mapped by Ibisch et al. (2016) matches our findings that RAs tend to increase in density and size as latitude increases. Recently, Pouteau et al. (2021) found that generally, threats to endemic species are lower and less severe in countries that have relatively more and larger RAs.

4.4.2. Southern Ontario

Logging and conversion of forest to agriculture starting in the mid-1700's left only 6% cover of forests standing in southern Ontario (9.2% of the province) by 1920 (Henry and Quinby, 2021) where today, 94% of Ontario's 13 million people live. These development activities were not possible without roads and were the primary historical drivers of RA loss resulting in only 4.2% (343,121 ha) cover of RAs in the region today, which is far lower than RA cover in Ontario's AOU (42.1%) and Far North (95.6%). Conversion of wetlands to agricultural use in southern Ontario resulting in the loss of roughly 1.5 million ha of wetlands has also led to the significant loss of RAs in southern Ontario (Snell, 1987). The best pines and oaks from the forests of the region were exported to the European timber market, many of the remaining forests burned by accidental fires facilitated by dry logging slash, land was cleared for farming or to make potash using fire, and stumps were pulled to create agriculture-friendly fields (OMNR, 1999). As a result, today less than 0.07% of southern Ontario is composed of original native forests (FON undated). However, since the early 1900's, second-growth forests in this region have increased to about 25% regional cover (ECO, 2018), which is more than three times lower than the roughly 90% original cover of the pre-settlement forests in southern Ontario (Schmitt and Suffling, 2006).

Table 6
Decline of forest dominance types in the human matrix of the bancroft minden forest management unit (difference = 1987 FRI – 2007 FRI).

Forest Dominance Type	% Decline	Forest Loss 1987 to 2007 (Ha/yr.)	1987 FRI (Ha)	2007 FRI (Ha)	Difference (Ha)
American beech	82	128	3138	569	2570
larch	70	75	2126	632	1494
white cedar	57	1492	52,506	22,656	29,850
sugar maple	13	1856	285,684	248,556	37,128
eastern hemlock	12	110	18,578	16,368	2210

4.4.3. Area of the undertaking

At 43.8 million ha in size, the AOU (Fig. 3) occupies almost half (49.1%) of Ontario, is five times larger than southern Ontario, and is ~5.7 million ha larger than the Far North. At 42.1% cover (~18.4 million ha), RAs in the AOU are ten times more abundant than in southern Ontario (4.2%) but less than half as abundant as RAs in the Far North (95.6%). Our study shows that about 58% (~42% RA cover) of the natural forests once found in the AOU have been removed or degraded by human activity. Similar findings of forest loss or degradation following decades of road building and logging activities in central Ontario have also been documented by Jackson et al. (2000) and Drever et al. (2010).

One of the first landscapes to be developed in the AOU was the Algonquin Park area, located in the southern portion of the region. Logging and associated construction of linear transportation corridors (e.g., dirt roads, horse-team trails) in the Park began around 1830 when regulations only permitted the logging of red and white pine trees. However by 1913, new regulations permitting the harvesting of all tree species (Henry and Quinby, 2021) facilitated the further development of timber trails, dirt roads and eventually the gravel roads that now cover ~5500 km of Algonquin Park (Quinby, 2021). This transportation network supports industrial logging that continues within two thirds of the Park, which at minimum has resulted in the decline of 13 tree species (AES, 2010), most of which have high ecological and economic value. In addition, the direct and indirect impacts of roads have lead to potentially permanent reductions in forest biomass accumulation (Thompson et al., 2006) through the degradation of tree gene pools (e.g., white pine, red pine) due to high-grade logging, and through the loss of site productivity (nutrients, soil structure, etc.) resulting from logging equipment disturbances (Freedman, 2018).

4.4.4. Far North

At 41.6% of the province, Ontario's Far North has extremely low road density resulting in RAs making up 95.6% of the region (~35.5 million ha). The Far North is home to ~24,000 people from 31 First Nations communities typically accessible only by air or winter roads (Wilkinson and Schulz, 2012), was established as a distinct region of Ontario in 2010 when the *Far North Act* (Province of Ontario, 2010) was passed into law, and is among the largest, most intact landscapes in the world (FNSAP, 2010). It supports more than 200 sensitive species including a threatened population of woodland caribou (Wilkinson and Schulz, 2012) and it contains coastal areas of the Hudson Bay Lowlands, which are among the most important global habitats for migratory shorebirds and waterfowl (Bumstead, 2021). Peatlands, non-forested bogs and fens, occupy the northern half of the Far North region storing ~36 Gt of carbon (McLaughlin and Webster, 2013) whereas boreal forests dominate in the southern half. The peatlands of the Far North make up 75% of the Hudson Bay Lowlands, which is the largest peatland complex in North America with the southern-most distribution of non-alpine permafrost. In northern portions of the Lowlands, climate warming has accelerated thawing of permafrost creating wetter peat resulting in increased methane emissions, whereas increased evapotranspiration and drier peat has accelerated CO_2 losses through increased decomposition in the southern Lowlands (McLaughlin and Webster, 2013).

The *Far North Act* prioritized the protection of areas of cultural and natural heritage value by requiring that at least 22.5 million ha (~60% of the region) be set aside within an interconnected ecological network, and that the maintenance of biodiversity, ecological integrity, and the storage and sequestration of carbon be ensured. The *Act* also provides for community-based land use planning by establishing a process requiring First Nations and the provincial government to work together; to support local environmental, social and economic values; and to ensure adherence to Aboriginal and treaty rights. Concerned over development restrictions of the *Act*, the Ontario government has committed to repeal the *Act* (Northern Ontario Business, 2021) in order to accelerate extraction of mineral deposits of chromite, nickel-copper-platinum-palladium, copper-zinc, gold, titanium-vanadium, and diamonds in the *Ring of Fire* region (Noront Resources, 2021). However, opposition from some Far North First Nations has resulted in the declaration of a moratorium to stop development of and access to the *Ring of Fire* (Friedman, 2021). With ~96% of the Far North in the roadless condition and supported by legislation that provides First Nations with decision-making input on potential local development projects, the prospect for maintaining a relatively healthy landscape in the Far North is much higher than elsewhere in the province.

4.5. RAs and the HM are different in the Bancroft Minden FMU

Compared to the HM, RAs in the BMFMU had twice as much wetland cover (9.6%) and 1.2x more old-growth forest indicating that, all other variables being equal, they support higher amounts of carbon and biodiversity (FAO and UNEP, 2020; Drever et al., 2021; Struzik, 2021; Sothe et al., 2022). However, all other variables were not equal in this particular landscape, chief among them were rock at 7.0% higher and productive forest at 5.0% lower in the RAs relative to the HM (Table 4). In the HM relative to RAs, agriculture (1.0% higher), water (1.2% higher), and human infrastructure (4.0% higher) land types generally store low amounts of carbon, which totals to about half (6.2%) of the 12% cover in RAs with low carbon storage capacity (e.g., rock barrens) resulting in 5.8% more low-carbon land types in RAs. More detailed studies using remote sensing imagery as well as field data are required to quantify carbon stores in RAs relative to the HM, however, since RAs generally have higher amounts of wetland and old-growth forest, it is likely that they also sequester and store greater amounts of carbon relative to the HM.

The higher amounts of undisturbed habitat including more wetlands, rock barrens, and old-growth forests in RAs relative to the HM where human infrastructure, agriculture, and logging are common occurrences resulted in higher quality habitat and higher biodiversity in RAs (Drever et al., 2010; OMNR, 2010; FAO and UNEP, 2020). The greater amount of forest dominated by red oak (14.2% higher) and white pine (8.9% higher) in RAs is not surprising given the high market value of these tree species and the aggressive exploitation of them within the HM for more than 150 years (Dey and Parker, 1996; Thompson et al., 2006; Drever et al., 2010). Given the long-established logging industry in the region, it is also not surprising that historical data showed the precipitous decline of three forest types in the HM over a 20-yr. period including American beech forest (82% decline), larch forest (70% decline), and white cedar forest (57% decline); and that two forest types declined less severely including sugar maple forest (13% decline) and eastern hemlock forest (12% decline). The high market value of sugar maple and white cedar also helps to explain their high area losses over the 20-yr. period with declines of 37,128 ha for sugar maple forest and 29,850 ha for white cedar forest in the HM.

4.6. RAs are the foundation for new protected areas

In the face of unprecedented threats from human development and in order to "*preserve the last remaining undeveloped forests as a home for wildlife, a haven for recreation and a heritage for future generations*" (Sierra Forest Legacy, 2021), the Clinton Administration (USA) set aside 23.7 million ha of RAs in 2001 (Turner, 2006). Codifying federal protection of RAs into law on U.S. Forest Service lands would increase the number of parks and reserves located at lower elevations, expand ecological (genes, species and habitat) representation, and increase the number of parks and reserves that are large enough to support self-sustaining wildlife populations (Develicei and Martin 2001).

A similar result would occur if Ontario's remaining large RAs were added to the Ontario Protected Areas System (Davidson et al., 1999). However, there is no federal or provincial RA legislation applicable to Ontario where 2.8 million ha of RA were recently lost between 2005 and 2020 contributing to substantial and rapid loss of biodiversity, ecological integrity, stored carbon, recreational resources, etc., that should be curbed in the next eight years if Ontario is to meet the federal "30% protected by 2030" target (Woodley et al., 2019; CPAWS, 2021). Currently, only 10.7% of Ontario's lands and waters are protected in Ontario's Protected Areas System (OMNDMNRF, 2021b), which requires an additional 20 million ha of protected area to reach 30% protection.

In order to assess the ecological integrity of Ontario's remaining pristine landscapes, and to increase the size and robustness of the Ontario Protected Areas System, Davidson et al. (1999) developed a Wilderness Quality Index (WQI) that was "*simple, logical, practical and user-friendly, and that… reflect[ed] society's values and measure[d] physical characteristics that people attribute to wilderness.*" This was necessitated by an outdated classification system that did not effectively address questions and issues posed by landscape conservation efforts in the face of accelerating human impacts. For example, the Hills' classification system (Crins et al., 2009), which is the standard biogeographical framework for conducting regional and provincial ecological assessments in Ontario, does not adequately address aquatic ecosystem representation or geological representation (Davidson et al., 1999). Ideally, the WQI would allow managers to rate a site's value as wilderness; monitor ecological integrity; complete the Ontario Protected Areas System; address the need to protect, restore, and monitor wilderness characteristics in managed landscapes; develop and implement wilderness policy; and develop, market and manage a wilderness-based ecotourism industry.

As the analytical mapping component of the WQI, Davidson et al. (1999) developed a geospatial model to quantify and describe the size, extent, historical impacts, threats to, and composition of remaining wilderness areas in the province. The coincidence of "*large roadless blocks*" and "*representative gap sites*" were used to identify and rank the ecological value of unprotected landscapes. The largest RAs were considered to be candidate wilderness parks while smaller RAs within the human-dominated portion of the landscape represent opportunities to create small parks and to manage for ecological integrity through impact mitigation and location control. The primary spatial patterns resulting from their mapping were also observed by Ibisch et al. (2016) and by our RA mapping indicating that, only a few small fragments of wilderness remain in southern Ontario; across the length of the Canadian Shield from east to west, RAs become more frequent and larger; and at the northern extent of the AOU where road density is low, isolated blocks gradually coalesce into a few large contiguous RAs "*delineating Ontario's wilderness frontier*" (Davidson et al. 1999).

Whereas the Davidson et al. (1999) wilderness classification system was never refined and applied, it remains as the first attempt in Canada to operationalize the concept of RAs to complete the next phase of building a provincial protected areas system. The mapping results from our study can serve as the foundation for future studies aimed at better understanding the structure, composition, and history of RAs, and the roles they play in protecting biodiversity, ecological integrity, and landscape resiliency at local to global levels.

Although little RA data are available for other jurisdictions, it is likely that very few others (e.g., countries, provinces, states) can claim as much RA as Ontario, both in absolute (ha) and relative (%) terms. If all remaining 18.5 million ha of RAs in Ontario's MFR were designated as parks and reserves, Ontario would achieve 92.5% of the 30 × 30 protection goal. And, because the province has already made legal commitments to provide forest industry logging access to some forested areas up to the year 2031 (OMNDMNRF, 2022), unallocated portions of RAs (no SFL agreements) could be designated as parks and reserves without breaking legal allocation agreements with forest industry. However, not all unallocated RAs will qualify as high quality parks and reserves due to factors such as small size, elongated shape, located outside of major conservation corridors, over-representation, etc. Thus, a protected areas gap analysis and subsequent ecological network assessment with the goal of adding 20 million ha to the Ontario Protected Areas System is needed to provide a set of candidate parks and reserves with the highest levels of ecological integrity and native biodiversity (Jetz et al., 2021) combined with the provision of ecosystem services important to people (Mitchell et al., 2021).

5. Conclusion

The challenge is clear – to minimize global temperature increases and to protect robust examples of Ontario's biodiversity and ecological integrity, scientists and the federal government recommend the addition of roughly 20 million ha (~20% of the province) to the Ontario Protected Areas System by the year 2030. However, given forest industry's focus on removing trees from the forested portions of RAs (almost 100% public land) and government's reliance on industry to provide jobs along with tax and stumpage revenue, it may be unwise to assume that a resource extraction industry monitored by a government dependent on revenues from that industry can achieve this goal given the clear conflict between the logging of native forests versus protecting biodiversity and ecological integrity. For example and as evidence of this skepticism, between 2005 and 2020 RAs in Ontario's MFR declined by 187,175 ha/yr. resulting in a loss of ~2.8 million ha of RA over this 15-yr. period.

The loss of RAs from road building and use, logging, and associated activities over the last century have contributed to the near total collapse of the woodland caribou population in Ontario at a mean rate of habitat loss of ~300,000 ha/yr. At a predicted rate of loss of ~3.7 million ha/decade starting in 2030, RAs in Ontario's MFR will become depleted by ~2090-2100, which is also a few decades following the potential extirpation of Ontario's native woodland caribou population if current conditions do not change. To maintain and restore Ontario's declining RAs and native caribou population, stakeholder engagement must grow to include more ENGOs, educators, students, scientists, naturalists, and recreational users (hikers, canoeists, backpackers, skiers, etc.) in order to collect key field and remotely sensed information for conducting natural heritage analyses, to educate the public about threats to forest landscape integrity, to advocate for effective long-term management through the provincial forest management planning process, to propose land-use designation changes from general use public land to parks and reserves and to monitor RAs.

Given the absence of a provincial strategy to reach the 30 × 30 goal for expansion of the protected areas system, we propose application of an RA assessment and monitoring strategy proposed by Ontario government scientists more than two decades ago that is rapid and would potentially result in minimal interference to existing legal logging-allocation agreements. We have completed the first step in this process – mapping the remaining RAs in the province. Unlike many political jurisdictions, expanding the parks and reserves system using the substantial inventory of RAs is possible for Ontario since it can draw from roughly 54 million ha of RAs covering 60.6% of the province. This includes 210 RAs larger than 10,000 ha and 50 RAs larger than 50,000 ha, however, the occurrence of these large RAs is skewed heavily towards the northern portion of the province. In the south, where human densities are relatively high and where forestry has been active for at least two centuries, there are far fewer large- and medium-sized RAs. In these southern areas, significant ecological restoration efforts will be required to achieve protection of robust ecological networks.

The urgency of this work is motivated by recent findings that Ontario's MFR, covering 58.3% of the province, is now a source of atmospheric carbon suggesting that the forest carbon tipping point has been surpassed. The most immediate response possible to tip the carbon balance of Ontario's managed forests back to carbon accumulation is to allow forests, wetlands, and other pristine ecosystems within remaining RAs to continue providing the free service of carbon accumulation unimpeded by human activity. Rather than use budgets to build new roads that degrade and fragment native forests, funds could be used to improve tree regeneration and forest biomass production in second-growth forests. Finally, a huge portion of Ontario's native biodiversity will likely be associated with the remaining RAs. Therefore, remote sensing studies and field studies are urgently needed to assess biodiversity and ecological integrity in and around Ontario's remaining RAs, which continue to be degraded, fragmented and removed by logging.

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Declaration of Competing Interest

None of the authors have any competing interests.

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