



# A Canada-wide macro assessment of protected area connectivity

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## ABSTRACT

Protected areas have become increasingly important for preventing biodiversity declines. However, their effectiveness depends, in part, on how well they are connected with other viable habitats because maintaining and enhancing species movement is critical for population persistence. We used human footprint data to identify potential movement corridors (within maximum distances of 5 and 50 km) among Canadian protected areas. We then compared the degree of connectivity for government protected areas, private protected areas, Indigenous managed lands, and a control (randomly sampled lands). At a maximum distance of 5 km, compared to the control group, government protected areas had 5.6 times more connections, private protected areas had 5.1 times, and Indigenous managed lands (e.g., Indigenous Protected and Conserved Areas) had 4.8 times. At a maximum distance of 50 km, government and private protected areas had 2.6 and 1.4 times the number of connections than the control group, respectively, but Indigenous managed lands had fewer connections than the control. Among private protected areas, at both maximum distances, conservation agreements had approximately 1.3 times the number of connections than fee simple properties. Our results highlight differences in connectivity between protected area types and the disparity in connectivity between government protected areas and their non-governmental counterparts.

## 1. Introduction

It is widely acknowledged that the creation of protected areas (PAs) is one of the most effective ways to stem declines in biodiversity (Watson et al., 2014; Gray et al., 2016). As of 2020, 16.6 % of the earth's terrestrial area is now protected, a percentage that is projected to increase over the next decade (Protected Planet, 2020). However, aside from the total area that is protected, the strategic placement of PAs will be an important factor in determining their effectiveness for conserving biodiversity. For example, PAs have been shown to be impactful when situated in biodiversity hotspots (Pimm et al., 2018; Jenkins et al., 2015) and landscapes under intense pressure from human development (Geldmann et al., 2019). In addition to landscape context, the effectiveness of PAs will also depend, in part, on the ability of ecological corridors to enable and maintain the movement of organisms between suitable habitats otherwise separated by unsuitable areas. Safeguarding movement between populations can serve as a demographic rescue for small or declining populations (Tucker et al., 2018) and help maintain genetic diversity (Haddad et al., 2015; Jangjoo et al., 2016). How well current PAs are connected by such movement corridors, however, has

rarely been assessed (Saura et al., 2019; Saura et al., 2018; Ward et al., 2020).

To reach broadly accepted targets of having 30 % of terrestrial areas protected by 2030 (UNEP 2023; European Environment Agency, 2022), it has been argued that the participation of non-governmental organizations and Indigenous Peoples in the establishment and management of PAs will be needed. As of 2022, approximately 84 % of PAs worldwide are governed by national or subnational governmental agencies (UNEP-WCMC and IUCN, 2022). Additionally, at least 40 % of the global PA estate is made up of Indigenous lands managed under a range of governance mechanisms: from Indigenous-led conservation (e.g., Indigenous Protected and Conserved Areas) as well as co-management with state agencies in situations where Indigenous land rights are not recognized within protected areas (Garnett et al., 2018). In Canada, for example, as of 2021, 13.5 % of land has been protected (Environment and Climate Change Canada, 2021a) and 76.9 % of these PAs are government-run (UNEP-WCMC and IUCN, 2023). Of the remaining PAs in Canada, <1 % are managed by Indigenous Peoples, 18.4 % are managed by private organizations, and 3.2 % are managed through collaboration between a governmental organization and Indigenous

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Peoples or between government and non-governmental organizations (Environment and Climate Change Canada, 2016). Recent studies have provided evidence that Indigenous managed lands (IMLs) and private protected areas (PPAs) are located in areas of higher vertebrate diversity than government PAs (Custode et al., 2021; Schuster et al., 2019). However, how IMLs and PPAs in Canada contribute to overall protected area connectivity has not been assessed.

Few studies have assessed the degree of connectivity between alternatives to government protected areas (GPAs). As of 2022, there have only been three national or global analyses of connectivity that specifically include non-governmental PAs: one on PPAs across the contiguous U.S. (Bargelt et al., 2020), the second across 15 countries on five different continents (Palfrey et al., 2022), and the third at the global scale (Brennan et al., 2022). However, only the U.S. study (Bargelt et al., 2020) used a comprehensive database of PPAs, which was done by supplementing data from the World Database on Protected Areas with PPAs in the National Conservation Easement database (Bargelt et al., 2020; UNEP-WCMC and IUCN, 2022), the latter of which contains data on over 90 % of conservation easements run by NGOs (National Conservation Easement Database, 2022). On the other hand, the analysis across 15 countries (Palfrey et al., 2022) supplemented the world database on protected areas (UNEP-WCMC and IUCN, 2022) with PPAs from national databases. However, national databases are often incomplete. For example, the Canadian national database includes only 388 PPAs, a small fraction of the over 5000 known to exist (British Columbia NGO Conservation Areas Database Technical Working Group, 2021; Réseau de Milieux Naturels Protégés, 2021). Finally, the global analysis only included PAs larger than 35 km<sup>2</sup> (Brennan et al., 2022), which excludes the vast majority of PPAs (British Columbia NGO Conservation Areas Database Technical Working Group, 2021; Réseau de Milieux Naturels Protégés, 2021). Finally, while it has been shown that IMLs are situated in highly intact lands and have been shown to contain significant amounts of biodiversity (Garnett et al., 2018; Fa et al., 2020; Schuster et al., 2019), the connectivity of IMLs was not assessed in any of these studies.

In this paper, using the most comprehensive dataset to date of PAs in Canada, we estimate and compare the degree of connectivity between GPAs, IMLs, and PPAs and, for PPAs, between methods of land acquisition. Because the majority of IMLs are found in the largely intact northern parts of Canada with a much lower number of PAs than southern Canada, IMLs are unlikely to have a high degree of connectivity (Environment and Climate Change Canada, 2021b). In contrast, the vast majority of PPAs are in the south of Canada because that is where there is private land available for acquisition. The prioritization procedures NGOs use when securing PAs and the locations where land is actually available for procurement are the two main factors that contribute to the connectivity of PPAs. While prioritization procedures for PPAs are not always publicly available, in our dataset, 18 NGOs (representing over 60 % of PPAs with known conservation priorities) list connectivity as a priority in conservation planning. As of 2016, none of the 15 federal, provincial, and territorial organizations responsible for PA creation considered connectivity a priority (Environment and Climate Change Canada, 2016) and it was only as of 2022 that the government of Canada (Parks Canada Agency 2022a) and the United Nations (CBD, 2022) committed to conserving ecological corridors. Similarly, the idea of prioritizing ecological connectivity when procuring PAs has only recently been adopted by most NGOs so it is possible that these new procurement strategies have not yet affected the connectivity of PPAs.

## 2. Methods

### 2.1. Data collection and management

To create a dataset of terrestrial government protected areas (GPAs), Indigenous managed lands (IMLs), and private protected areas (PPAs), we used a set of predetermined criteria. We considered a protected area

(PA) to be any parcel of land over 0.09 km<sup>2</sup> that was spatially separated from other protected areas and had a distinct organization managing the property (in some cases lands were managed by groups that did not own the property) or ownership group from neighbouring protected areas. A maximum size of 0.09 km<sup>2</sup> was chosen because this was the resolution of the raster dataset used to measure human footprint on the landscape (Hirsh-Pearson et al., 2022). GPAs were considered to be any PA managed under a governmental organization that fell under an IUCN protected area category (Dudley, 2013). Spatial polygons of GPAs were acquired from the Canadian protected and conserved areas database (Environment and Climate Change Canada, 2021a). IMLs were considered any area that was protected or designated for protection under the management or co-management of a group associated with an Indigenous government, community, or non-governmental organization according to the Canadian protected and conserved areas database (Environment and Climate Change Canada, 2021a). PPAs were any land owned or managed by a non-governmental, non-Indigenous organization for the purpose of conservation. Because connectivity between protected areas is not restricted by national borders, we also included PAs in the United States (U.S.) within 50 km of the Canadian border as potential connections. Our definition of U.S. PAs was the same as Canadian PAs. Spatial polygons for U.S. PAs were obtained from the World Protected Areas Database (UNEP-WCMC and IUCN, 2022).

To obtain locations of IMLs, data were retrieved from two sources: (1) polygons in the Canadian protected and conserved areas database (Environment and Climate Change Canada, 2021a) whose management, co-management or ownership was listed as an Indigenous group, and (2) point data for proposed IMLs that have been identified on the Canadian government's Canada Target 1 Challenge website (Environment and Climate Change Canada, 2021b). We only included IMLs that were currently established or in the process of being established (listed under the *establishment* category). Because IMLs from the Canada Target 1 Challenge website only contained a point location (not a polygon or area), we created circular buffers around each point corresponding to the size of the protected area if it was given or, if the size was not given, a circular buffer of 50 km<sup>2</sup>, which was the average size of a GPA in Canada (Custode et al., 2021).

To obtain the locations of PPAs in Canada, we collected polygons from the two provincial/territorial PPA databases that were available: the British Columbia Non-Governmental Organization Conservation Areas database for PPAs in British Columbia (British Columbia NGO Conservation Areas Database Technical Working Group, 2021), and Le Réseau de Milieux Naturels Protégés for PPAs in Quebec (Réseau de Milieux Naturels Protégés, 2021). We then contacted individual conservation organizations across Canada and obtained polygons from the Nature Conservancy of Canada and 11 other NGOs (see Table S1 for a complete list). While supplementary data were not available for most provinces, PAs in Manitoba, Newfoundland and Labrador, Ontario and Prince Edward Island were found in national databases. Specific details about data cleaning can be found in Supplemental Material S1.

To create a control group, 10,000 points were randomly generated within Canada. In ArcMap (ESRI, 2019), a circular buffer was created around each random point, with the size of the buffer determined by randomly sampling sizes from existing PAs from our dataset (Schuster et al., 2019). To ensure randomly generated areas fit within the study area, any buffers that extended outside of the Canadian border were clipped, meaning that some polygons in the control group ( $n = 4$ ) had their size reduced for the analysis.

Human footprint data for Canada were obtained from Hirsh-Pearson et al. (2022; scale: 300 x 300m) and human footprint data for the U.S. were obtained from Venter et al. (2016; scale: 1000 x 1000m). To ensure that both human footprint datasets were at the same resolution, the Venter et al. (2016) dataset was resampled using the project raster tool in ArcGIS into 300 x 300 m pixels and then merged with the Hirsh-Pearson et al. (2022) dataset. In ArcGIS, the complete PA dataset was converted into a raster layer with a cell size of 300 x 300 m and then

merged with the human footprint raster. Each PA was then separated into its own shapefile using a Python script (Python Software Foundation, 2010; Patterson, 2016). Using ArcGIS and Python, buffers with a maximum radius of 5 km and 50 km were created around each PA shapefile. To reduce the computational requirement for the analysis, the raster layer containing PA ID and human footprint value was clipped with this buffer shapefile resulting in a raster file for each protected area that contained human footprint and PA information within a given maximum distance.

## 2.2. Identifying the degree of connectedness

To estimate connectivity between PAs, each focal protected area was defined to be structurally connected to another GPA, IML or PPA if it was possible to move between them via contiguous ‘intact’ land within the given maximum distance (5 km or 50 km). Land that had a human footprint value of 3 or less (out of a theoretical maximum of 66; Hirsh-Pearson et al., 2022) was defined to be ‘intact’ because prior research has shown anthropogenic pressure in areas with a human footprint of  $>3$  is an important predictor of extinction risk (Di Marco et al., 2018). If we used a method like circuit theory (Brennan et al., 2022), which describes the resistance to movement caused by landscape features lands, regions with larger human footprints would be considered resistant but still passable to movement. However, corridors connecting PAs with a high human footprint (HFP  $> 3$ ) can restrict an organism’s ability to move between PAs (Tucker et al., 2018) or potentially threaten their viability (Di Marco et al., 2018). Thus, we choose a metric which describes connectivity in a binary fashion (land is either passable or impassable) because it more accurately describes land where anthropogenic pressures restrict species movement and is easy to communicate among a variety of different stakeholders. This analysis was repeated twice, at maximum distances of 5 and 50 km, which allowed for an examination of the connectivity of protected areas at spatial scales that represent two different scales of dispersal: one for larger organisms such as birds and mammals and a second for invertebrates, amphibians, and small mammals. Previous analyses of connectivity have used larger maximum distances between connected PAs (100 km, 30 km and 10 km; Saura et al., 2017). However, we choose maximum distances 50 km and 5 km because they are more conservative estimates of dispersal distances. While previous research has also quantified connections to PAs that can only be reached by “stopping over” at intermediate PAs (Ward et al., 2020), to measure the number of unique PAs that an organism could potentially reach during dispersal, we chose to only measure connections to PAs within a specific distance of our focal PA.

To identify connections to protected areas, raster files for each protected area were converted into a matrix and a breadth-first search algorithm using R (S1; R Core Team 2021; Rahim et al. 2018; Zuse, 1972). A breadth-first search algorithm iterates through the cells in the matrix and identifies pathways between a focal object (the focal PA) and surrounding objects (PAs within a reachable distance of the focal PA). For each protected area, this algorithm was run starting with each cell along the perimeter of the protected area. After each iteration, the matrix was checked to see if all cells with a human footprint of  $<3$  had been reached. If this condition was met, the algorithm was stopped. After the algorithm stopped, a third matrix containing information on reachable intact cells and protected areas was converted to a raster and saved. For each saved raster file, the number of protected areas of each type was counted and stored in a data frame column corresponding to the protected areas ID.

## 2.3. Data analysis

We used the Mixed GAM Computation Vehicle with Automatic Smoothness Estimation package (mgcv; Wood, 2011) in R (R Core Team 2021) to perform generalized additive models to predict the variation in the number of connections for each protected area type for each

distance. In these models, protected area type (“PA type”: IML, GPA, PPA, or control), protected area size (“size”; km<sup>2</sup>), and area of protected land within the sampled radius (“APL”; km<sup>2</sup>) were included as linear predictors. We choose to control for PA size because smaller PAs have less constraints in their creation potentially making them easier to create in areas that are well connected to other PAs. To measure APL at the spatial resolution of our analysis (a 300 m  $\times$  300 m grid), APL was calculated in R (R Core Team, 2021) by multiplying the number of protected area cells by the cell size (90,000 m<sup>2</sup>). Additionally, to predict the effect that location of the focal PA might have on connectivity, we used a thin plate spline term as a predictor in all models. A thin plate spline is a type of smoothing spline that predicts the combined effects of two predictor variables on a response variable accounting for both predictor variables at the same time. In our model, the centroid x and y coordinates of the focal PA were used as predictor variables in the thin plate spline. While it is known that the south of Canada generally contains a high human footprint, we also chose to control for longitude because there are some areas, such as northern Alberta, that have much higher human footprint values than most other areas at the same latitude, while other areas, such as the far west of Ontario near the north shore of Lake Superior, have much lower human footprint values than most other areas at a similar latitude.

AIC selection was used to select a top model and all models within 2  $\Delta$ AIC were considered valid top models (Burnham et al., 2002). In cases where more than one model was within 2  $\Delta$ AIC and the simplest model only contained one less parameter, the simplest model was considered for reporting effect sizes (Burnham et al., 2002; Arnold, 2010).

## 3. Results

At the 5 km maximum distance, there were 2 top models: the full model containing PA type (IML, GPA, PPA, Control), PA Size, and the area of protected land within the sampled radius (APL) as linear predictors, and location (a thin plate spline); and a second model with the same predictors except PA size (Table S2). Here, we evaluate estimates from the second, simpler model. In this model, compared to the control group, GPAs (Table 1; Fig. 2) were predicted to have 5.6 times the number of connections, PPAs had 5.1 times the number of connections, and IMLs had 4.8 times the number of connections.

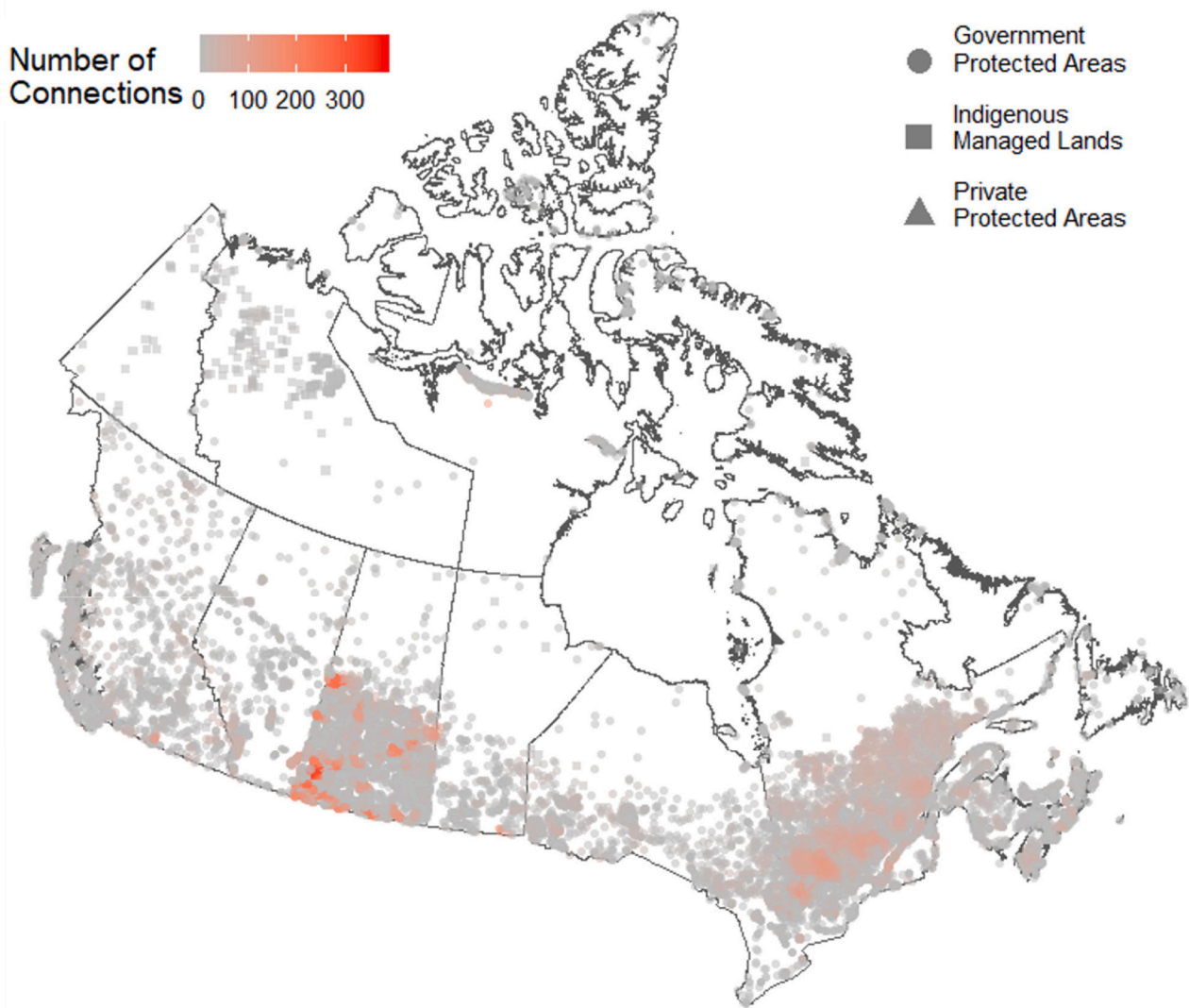
At the 50 km maximum distance, the top model was the full model with PA type, PA Size, and APL as linear predictors, and location (a thin plate spline; Table S3). In this model, compared to the controls, GPAs (Fig. 1; Table 2; Fig. 2) were predicted to have 2.6 times the number of connections, PPAs had 1.4 times the number of connections, and IMLs had 0.95 times the number of connections.

We then evaluated the number of connections by acquisition type

**Table 1**

Parameter estimates for the top generalized additive model to explain the number of connections within a 5 km maximum distance of each Canadian protected area. Predictors include protected area type (PA type: government protected area (GPA; the reference level), Indigenous managed land (IML), private protected area (PPA), control), size of focal protected area (size: km<sup>2</sup>), area of protected land within the 5 km maximum radius (APL: km<sup>2</sup>) and a thin plate spline (TPS) of the center x and y focal protected area coordinate. For linear predictors, the associated coefficient and 95 % confidence interval are given and, for the smooth term, the effective degrees of freedom (EDF) is given.

Parameter estimates		
Linear predictors	Coefficient	95 % CI
Intercept	0.848	(0.831, 0.8645)
PA type: IML	-0.156	(-0.326, -0.014)
PA type: PPA	-0.102	(-0.116, -0.088)
PA type: control	-1.728	(-1.767, -1.689)
APL	0.434	(0.423, 0.445)
<b>Smooth term</b>	<b>EDF</b>	
TPS	28.98	



**Fig. 1.** The raw number of connections of different types of protected areas across Canada within a 50 km radius. For this figure, to protect the confidentiality of private landowners, only fee simple private protected areas from the Nature Conservancy of Canada are shown.

**Table 2**

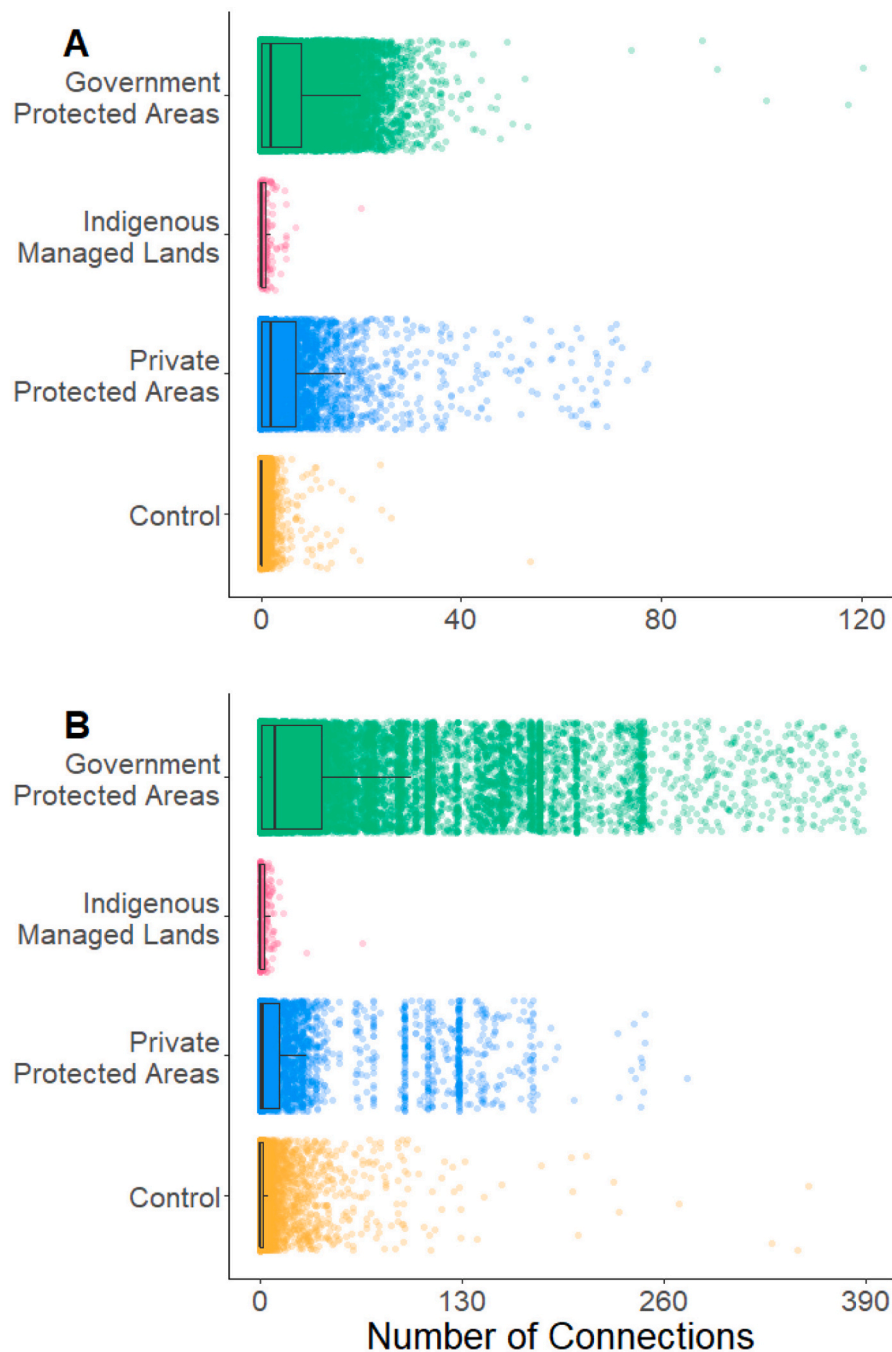
Parameter estimates for the top generalized additive model to explain the number of connections within a 50 km maximum distance of each Canadian protected area. Parameter estimates for the top generalized additive model to explain the number of connections within a 50 km maximum distance of each Canadian protected area. Predictors include protected area type (PA type: government protected area (GPA; the reference level), Indigenous managed land (IML), private protected area (PPA), control), size of focal protected area (size: km<sup>2</sup>), area of protected land within the 50 km maximum radius (APL: km<sup>2</sup>) and a thin plate spline (TPS) of the center x and y focal protected area coordinate. For linear predictors, the associated coefficient and 95 % confidence interval are given and, for the smooth term, the effective degrees of freedom (EDF) is given.

Parameter estimates		
Linear predictors	Coefficient	95 % CI
Intercept	1.949	(1.939, 1.959)
PA type: IML	-0.992	(-1.074, -0.911)
PA type: PPA	-0.619	(-0.626, -0.611)
PA type: control	-0.945	(-0.957, -0.934)
Size	-3.292 * 10 <sup>-4</sup>	(-3.375 * 10 <sup>-4</sup> , -3.209 * 10 <sup>-4</sup> )
APL	4.553 * 10 <sup>-4</sup>	(4.526 * 10 <sup>-4</sup> , 4.579 * 10 <sup>-4</sup> )
<b>Smooth terms</b>	<b>EDF</b>	
TPS	28.99	

within PPAs at both the 5 and 50 km maximum distances. The top model at the maximum distance of 5 km was the full model containing PPA type (fee simple; PAs directly owned by an NGO, conservation agreement; PAs owned by a second party but managed for the purpose of conservation by an NGO), PA Size, and APL as linear predictors, and location (a thin plate spline; Table S4). In this model, conservation agreements were predicted to have 1.4 times the number of connections of fee simple properties (Table 3; Fig. 3). At the maximum distance of 50 km, the top model was also the full model (above) with conservation agreements predicted to have 1.3 times the number of connections of fee simple properties (Table 4; Fig. 3).

#### 4. Discussion

In this paper, we have developed a method that simply and accurately compares connectivity between different protected area (PA) types. In Canada, we have demonstrated how this method can be used to highlight the current disparity connectivity between government protected areas (GPAs), Indigenous managed lands (IMLs), and private protected areas (PPAs). Given differences in PA connectivity, we consider why this discrepancy exists, how are results can help inform the management of existing PAs, and how our approach can help inform



**Fig. 2.** Boxplots showing the raw number of connections to other protected areas at maximum distances between connected protected areas of 5 km (A) and 50 km (B). Each boxplot represents a different protected area type (government protected areas, Indigenous managed lands, private protected areas, and control) with dots representing the number of connections of each protected area. The control group was generated by randomly sampling land throughout Canada.

future acquisition of protected areas.

There are likely several reasons for our finding that GPAs have a higher degree of connectivity than PPAs. The first is that, despite some of the larger NGOs prioritizing connectivity in their mandates, this is not the case for many smaller NGOs. In our database, while 25 % of PPAs were run by NGOs that explicitly mentioned connectivity in their strategic land acquisition statements, acquisition strategies for the majority of PPAs (59 %) were not publicly listed, meaning that land acquisition priorities were unknown. Of the remaining PPAs, which were run by NGOs that do not prioritize connectivity, there was a variety of other conservation priorities, including 386 PPAs (7 %) run by NGOs that focused on a specific region, 255 PPAs (4 %) run by NGOs that focused

on specific habitat types, 255 PPAs run by NGOs (4 %) that focused on specific species, and 466 PPAs (8 %) run by NGOs that focused their acquisitions only on islands. All of these may be highly beneficial in their particular context and, indeed, many NGOs with different priorities may be advantageous for the development of an effective national protected area network. However, none of these priorities, particularly ones with island mandates, would necessarily lead to PAs with a high degree of connectivity. The second reason is that, even though NGOs that prioritize PA connectivity own a large number of PPAs, the decision to consider connectivity in planning procedures has only happened recently, meaning that the focus on connectivity in priorities may not have had long enough to have a large effect on the current network of

**Table 3**

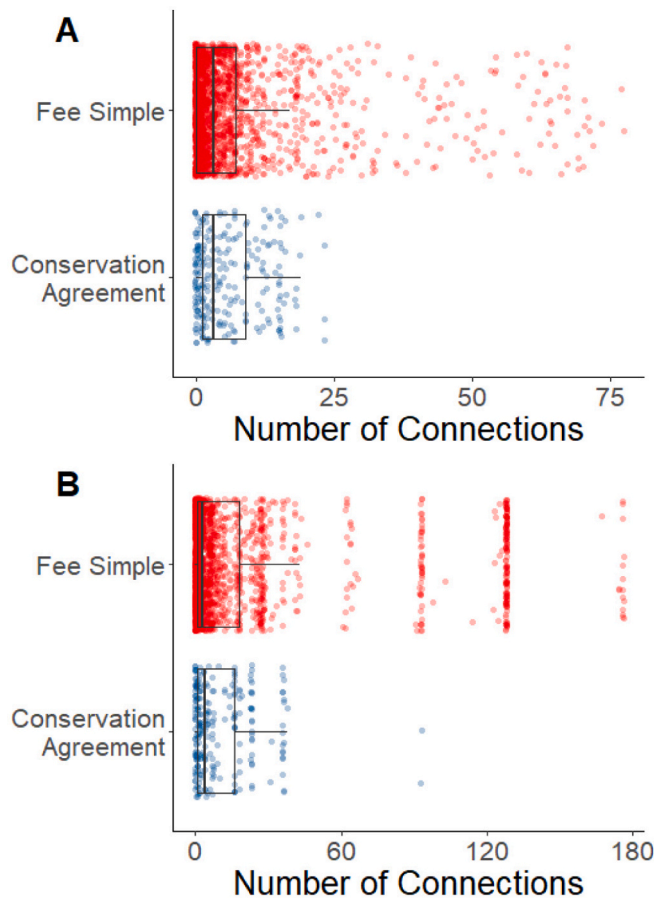
Parameter estimates for the top generalized additive model to explain the number of connections within a 5 km maximum distance of each Canadian private protected area. Parameter estimates for the top generalized additive model to explain the number of connections within a 50 km maximum distance of each Canadian protected area. Predictors include protected area type (PA type: conservation agreement (the reference level), fee simple), size of focal protected area (size: km<sup>2</sup>), area of protected land within the 5 km maximum radius (APL: km<sup>2</sup>) and a thin plate spline (TPS) of the center x and y focal protected area coordinate. For linear predictors, the associated coefficient and 95 % confidence interval are given. For the smooth term, the effective degrees of freedom (EDF) is given.

Parameter estimates		
Linear predictors	Coefficient	95 % CI
Intercept	1.197	(1.129,1.264)
PA type: fee simple	-0.330	(-0.399,-0.261)
Size	-0.052	(-0.056,-0.048)
APL	0.029	(0.028, 0.030)
<b>Smooth terms</b>	<b>EDF</b>	
TPS	28.95	

**Table 4**

Parameter estimates for the top generalized additive model to explain the number of connections within a 50 km maximum distance of each Canadian private protected area. Parameter estimates for the top generalized additive model to explain the number of connections within a 50 km maximum distance of each Canadian protected area. Predictors include protected area type (PA type: conservation agreement (the reference level), fee simple), size of focal protected area (size: km<sup>2</sup>), area of protected land within the 50 km maximum radius (APL: km<sup>2</sup>) and a thin plate spline (TPS) of the center x and y focal protected area coordinate. For linear predictors, the associated coefficient and 95 % confidence interval are given and, for the smooth term, the effective degrees of freedom (EDF) is given.

Parameter estimates		
Linear predictors	Coefficient	95 % CI
Intercept	2.266	(2.212, 2.320)
PA type: fee simple	-0.249	(-0.297,-0.202)
Size	3.174*10 <sup>-3</sup>	(2.507*10 <sup>-3</sup> , 3.840*10 <sup>-3</sup> )
APL	5.000*10 <sup>-5</sup>	(1.116*10 <sup>-5</sup> , 8.886*10 <sup>-5</sup> )
<b>Smooth terms</b>	<b>EDF</b>	
TPS	28.96	



**Fig. 3.** Boxplots showing the raw number of connections of fee simple private protected areas and conservation agreement private protected areas to other protected areas at maximum distances between connected protected areas of 5 km (A) and 50 km (B). Each boxplot represents a protected area type (conservation agreement and fee simple) with dots representing the number of connections for each protected area.

PPAs. The third is that many PPAs are in highly developed regions of the country (Environment and Climate Change Canada, 2021a; Hirsh-Pearson et al., 2022), which means they tend to have a low degree of connectivity compared to protected areas in other regions because of

high human footprint values surrounding the protected area. Additionally, NGOs are only able to create PAs in locations where landowners are willing to sell land or create conservation agreements which limits their options for creating PPAs in locations that are important for connectivity. That said, NGOs play an important role in protecting these highly developed landscapes because they are often small parcels of privately owned land that governments are not always able or willing to protect (Palfrey et al., 2022).

Similar to our previous research, which showed that conservation agreements tended to be located in areas of higher species diversity than fee simple properties (Custode et al., 2021), we found that conservation agreements also had higher connectivity than fee simple properties. One possible reason for this, which we articulated in the introduction, is that conservation agreements can be more easily established than fee simple properties. For example, in urban areas, due to high land values, conservation agreements on already-owned land are a much more attainable type of PA than a fee simple property, which requires a new purchase (Morris, 2011). Similarly, in central Canadian ranch lands, conservation agreements have been used to conserve areas that enable movement between PAs because the land is not typically available to be directly acquired by NGOs (Bendickson, 2009). The ability to create conservation agreements in areas that would otherwise be difficult to directly purchase allows NGOs to more effectively utilize their land prioritization procedures for conservation.

IMLs had a lower degree of connectivity than all other PA types. We stress, however, that this does not mean that these IMLs are not important for the development of Canadian conservation networks. The majority of IMLs are in the northern half of Canada, which is relatively intact but is also relatively unprotected compared to the southern half of Canada. While the low density of PAs in northern Canada likely drives the low number of connections to and from northern-based IMLs, this also implies that IMLs are safeguarding regions of Canada that are relatively unprotected. IMLs also on average over 6 times larger than GPAs that even though they are not connected to other PAs it may still be possible for organisms to disperse within most IMLs. Furthermore, because of the high level of intactness in the northern half of Canada (Hirsh-Pearson et al., 2022), IMLs are still connected to intact unprotected habitats even if they aren't connected to other nearby PAs.

While the definition of IMLs for this study only included IMLs that are owned or managed by Indigenous groups for the purpose of conservation, there are other types of IMLs and Indigenous conservation strategies not included in this analysis that could potentially be important for assessing the connectivity of protected areas, including Indigenous lands under customary forms of conservation governance (Artelle et al., 2019; Indigenous Circle of Experts, 2018). Previous studies have

used a broader definition of IMLs, which includes all land owned or managed by Indigenous groups (Schuster et al., 2019; Fa et al., 2020). While broadly-defined Indigenous managed lands have been shown to contain a relatively high number of species (Schuster et al., 2019) and are in intact landscapes (Fa et al., 2020), we choose to exclude them from our analysis because these lands are not legally bound to protect biodiversity. Another Indigenous-led conservation initiative that was excluded from our analysis was Indigenous Guardians programs (Environment and Climate Change Canada, 2022), which enable members of Indigenous nations to formally monitor and enforce conservation throughout their territories as well as support the cultural heritage of their communities (Artelle et al., 2019; Reed et al., 2021). While Indigenous Guardian programs are important in Canadian conservation and may eventually lead to the creation of formal Indigenous Protected and Conserved Areas (IPCAs), they were excluded from our analysis because they currently are not legally bounded areas restricted for conservation. Finally, the management strategies of many GPAs in Canada are moving towards co-management with Indigenous Peoples meaning that many PAs currently considered GPAs in our analysis could soon meet criteria to be considered IMLs (Parks Canada Agency, Government of Canada, 2022b). With changes to GPA management strategies and governmental commitments to increase Indigenous-led conservation globally (CBD 2022; Environment and Climate Change Canada, 2021c), the importance of IMLs in the connectivity of Canadian and global PAs will be crucial to assess in the near future. Indigenous-led conservation has been recognized as essential to the achievement of ambitious conservation targets agreed to in the recent Kunming-Montreal Global Biodiversity Framework, including Target 3 which upholds the rights of Indigenous Peoples over their traditional territories in area-based conservation (CBD, 2022).

By analyzing the connectivity of individual PAs, our analysis describes connectivity in a way that can be used to inform the management of existing PAs and help inform the planning and acquisition of new PAs. For example, if an organization manages a PA which is isolated, they can implement strategies such as the translocation of organisms into a PA to prevent a loss of genetic diversity. In contrast, a PA with a high degree of connectivity may be the optimal place for species reintroductions as it allows for easy movement to surrounding habitats. Our methodology could also enable an organization to easily measure the degree of connectivity for a planned future PA, helping to determine its efficacy for conservation. A proposed PA can be added to an existing raster layer and a search algorithm can be quickly used to determine how many PAs it is connected to. Additionally, the simplicity of counting the number of PAs that are interconnected with a focal PA means that this information could be easily used when used in fundraising strategies.

To assess PA connectivity across Canada, this analysis was purposely designed to describe connectivity for a broad range of taxa. However, this also means that we almost certainly missed some of the nuances associated with habitat connectivity for specific species. For example, the human footprint data used for this analysis assigned areas within 0.5 km of a roadway a human footprint value of 8 (Venter et al., 2016), meaning that they were considered 'impassable'. While roadways are difficult or impossible to cross for many taxa (e.g. road mortalities in amphibians can cause up to a 90 % decline in population size; Hels and Buchwald, 2001), other species, such as birds, are not affected by roads to nearly the same extent. Our analysis also considered aquatic areas impassable but, of course, many species are capable of crossing waterways. Conversely, other natural barriers, such as mountains and steep inclines, were also not considered as barriers in our analysis but could affect species movement (Trense et al., 2021). While our assessment of the connectivity of Canadian PAs allowed us to broadly compare connectivity between PA types, the effective planning, and creation of PAs for specific species or regions may require a more fine-scale, and sometimes taxon-specific, approach.

Increasing the connectivity of non-government PAs will be key in ensuring an effective national network of protected areas. In Canada,

both IMLs and PPAs are found in areas with similar or higher species diversity compared to GPAs (Schuster et al., 2019; Custode et al., 2021). However, our analysis found that both PA types had lower connectivity than GPAs. Because enabling the immigration and emigration of organisms from habitat patches is one component for ensuring their long-term survival (Tucker et al., 2018; Haddad et al., 2015; Jangjoo et al., 2016), it will be important to create PAs, especially non-governmental PAs, that not only have a high degree of connectivity but also enable species movement between already existing PAs that currently have a low degree of connectivity.

As part of a global push to ensure the protection of areas important for ecological movement (CBD, 2022), non-governmental PAs are becoming increasingly important in Canadian and global conservation. While Indigenous-led conservation (CBD, 2022), PPAs and OECMs have all received increased funding in the past few years, there remain few analyses which quantify the connectivity of these PAs (Bargelt et al., 2020; Palfrey et al., 2022). In this paper we have demonstrated a method which describes the connectivity of non-governmental PAs at a small enough spatial scale to include PPAs which are often excluded from larger scale analyses and described differences in connectivity across PA types. Additionally, our analysis is the first to assess the connectivity of IMLs at a national level. While we have only conducted this analysis in Canada, similar analyses should be conducted globally to quantify the contributions of non-governmental PAs to connectivity.

#### Declaration of competing interest

The authors of this manuscript have no competing interests to declare.

#### Data availability

We do not have permission to share data for the private protected areas used in this analysis. Data for Indigenous managed lands and government protected areas is available upon request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2023.110246>.

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