Status of woodland caribou (*Rangifer tarandus caribou*) critical calving habitat in the traditional territory of Waswanipi

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by

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1. Introduction

Caribou and reindeer herds (*Rangifer tarandus*) throughout North America and Eurasia have undergone important declines (Vors and Boyce, 2009) in the wake of rapidly changing environments. In Canada, boreal woodland caribou (*Rangifer tarandus caribou*) are particularly vulnerable given that the perennity of their populations depends on large areas of undisturbed old-growth boreal forest which are also prized for their tremendous value to forestry and forestry-related industries. Northward expansion of commercially harvested forests and resource extraction industries in the past decades has resulted in rapid loss of old-growth forests and caused important declines in many boreal woodland caribou herds of Canada (Festa-Bianchet et al., 2011).

In response to rapidly decreasing populations of several boreal woodland caribou herds, the Government of Canada's Committee on the Status of Endangered Wildlife in Canada (COSEWIC) listed it as a "Threatened" species under the *Species at Risk Act* in the year 2000 (COSEWIC, 2014, 2002), prompting the creation of a recovery strategy by Environment and Climate Change Canada (EC, 2012; ECCC, 2020). The Government of Québec also designated boreal woodland caribou as a "Vulnerable" species in 2005 and has since created its own recovery strategy (MFFP, 2013; MRNF, 2008). However, implementation of landscape planning and management strategies that reconcile forestry-based economies with the habitat requirements of species with large individual and herd ranges like boreal woodland caribou remains a challenge, and woodland caribou populations continue to decline throughout their boreal range to the present day (ECCC, 2020).

Unlike their migratory counterparts, boreal woodland caribou ("woodland caribou" or "caribou" hereafter) disperse prior to calving, selecting isolated areas characterised by mature open coniferous forests, wetlands, and peatlands (Bergeron, 2012; ECCC, 2020; Rudolph et al., 2012). This spacing-out strategy requires large areas of undisturbed habitat (Lesmerises et al., 2013) and helps reduce the risk of predation by reducing population densities during calving. However, forestry-impacted landscapes disrupt this strategy through several interacting mechanisms: habitat loss and transformation, apparent competition, and increased predator mobility. Logging invariably leads to loss of old growth forests. Loss of such habitats reduces forage availability in winter (Smith et al., 2000), which exacerbates what is already a period of nutritional and energetic stress for parturient females. Cutblocks and forestry-managed landscapes also promote the growth of younger forests and shrublands, a process that has led to an increase in moose (*Alces alces*) populations adjacent to woodland caribou habitats (Bergerud et al., 2008). In turn, higher moose density leads to increased predator density and increased predation pressure on caribou (Serrouya et al., 2017), a process called apparent competition. Finally, the problem of habitat loss and increased predator density is further compounded by logging roads and other linear disturbances (*e.g.* hydro lines, seismic lines), which facilitate predator mobility and access into core calving areas (Whittington et al., 2011). The cumulative effects of anthropogenic disturbances on caribou ranges has resulted in lower caribou population recruitment rates and, as a consequence, the persistence of several populations is threatened (EC, 2009).

In the Eeyou Istchee and James Bay territory there are three herds of woodland caribou: the Assinica, the Nottaway, and the Témiscamie herds. Their populations face mounting pressure from habitat disturbances, especially in the southern part of their ranges where forestry is more prevalent. As of 2013, it is estimated that disturbances impact 51%, 33%, and 47% of the ranges of the Assinica, the Nottaway, and the Témiscamie herds, respectively (Rudolph, 2017; Rudolph et al., 2017). The most severely impacted range is that of the Assinica herd, which overlaps significantly with the traditional territory of the Cree First Nation of Waswanipi (CFNW). Due to the traditional importance of woodland caribou, the status of these herds in the face of rapidly changing habitats is of great concern to land users in Waswanipi and indeed throughout Eeyou Istchee (Cree Regional Authority, 2010).

2. Objectives

Previous studies on herds in Waswanipi (and Eeyou Istchee) confirm that the winter, spring, calving, and post-calving seasons are the periods of the year with the greatest mortality due to predation (Rudolph et al., 2012). It is during this critical period of the year that habitat selection can have the greatest consequence on demographic parameters such as female survival and calf recruitment (Pinard et al., 2012). Given the vulnerability of calves to predation in the days following birth, calving ranges constitute the most sensitive areas of a population's overall critical habitat (EC, 2011). As mandated by the Cree First Nation of Waswanipi, this study aims to identify and describe critical calving habitats within the Waswanipi territory (see Figure 1) between 2004 and 2020. Specifically, the primary objectives of this study are to:

1) ***Identify individual calving ranges within Waswanipi.***

2) ***Identify the habitat characteristics of calving ranges using habitat selection analysis.***

3) ***Identify critical calving habitats within Waswanipi and describe their status (quantity and quality) over the course of study period.***

4) ***Provide recommendations on the protection of existing calving habitats.***

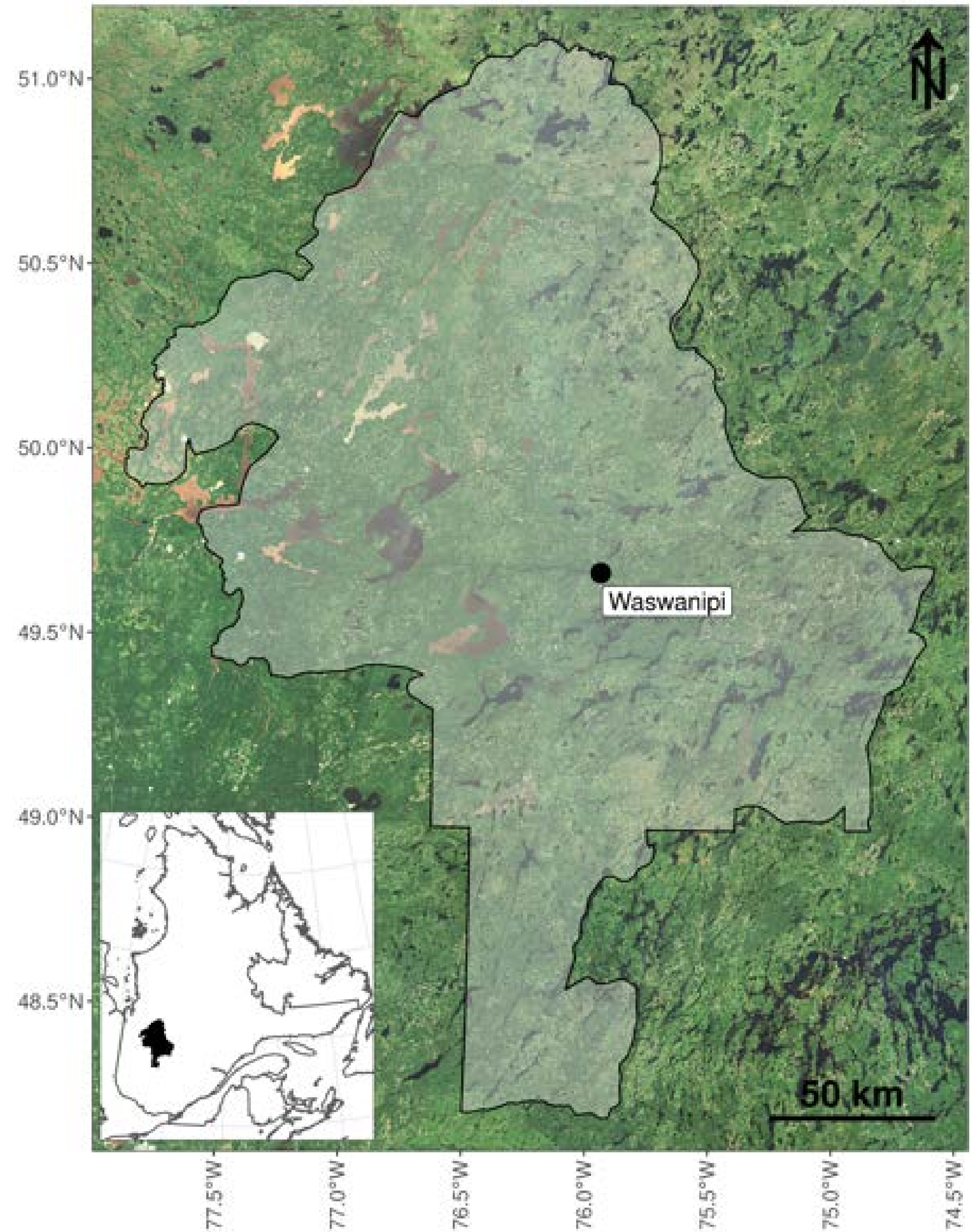

Figure 1. Map of study area encompassing the traditional territory of the Cree First Nation of Waswanipi. The inset shows the location of the region within the province of Quebec. Basemap is a Sentinel-2 RGB annual median composite.

3. Methodology

3.1 Caribou Telemetry Data

Telemetry data collected from female woodland caribou between 2004 and 2020 was used to (i) identify calving events and (ii) estimate the calving range associated to each calving event.

Through an ongoing GPS collar program, the Ministère des Forêts, de la Faune et des Parcs (MFFP) has been monitoring the GPS locations (*i.e.* relocations) of individuals from several herds, including three herds in the boreal forests of Quebec within the Eeyou Istchee territory: the Assinica, the Nottaway, and the Témiscamie herds. A subset of these data, collected within the Waswanipi region, was released to the Cree First Nation of Waswanipi (CFNW) by the MFFP. For the purposes of this study, only relocation data from female caribou during calving were retained for subsequent analysis. To ensure data quality, duplicate observations and extreme outliers were censored. Extreme outliers were determined based on thresholds in the distribution of speeds between two successive relocations (>4 km/h) and the distribution of net square displacement (NSD) since initial capture (>15000 sq km).

Calving events were identified by inspecting each female's annual relocation data using (i) maps of trajectories, (ii) time series of movement speed, and (iii) time series of NSD. Given the high temporal variability of seasonal cycles and behaviours, the beginning and end of individual calving events were identified through exhaustive inspection of individual collar data. The period of interest was limited to the spring, calving, and post-calving seasons which were selected using dates identified by previous studies for these caribou herds (Rudolph et al., 2012; Rudolph and Drapeau, 2012), from approximately the 95th to the 210th day of each year. To further reduce the influence of outlier observations during this period, the speed between successive relocations and the NSD since the first observation of spring was estimated using a moving average in a 48-hour sliding window. A female was considered to be calving if her trajectory exhibited temporary residency in a small area, very low mean movement speeds (almost zero km/h), and stable mean NSD. Using the time series of relocations associated with each calving event, a female's calving range was estimated using a minimum convex polygon (MCP) containing 95% of relocations. All data cleaning operations and computations were performed in R (R Development Core Team, 2020) and the MCP was estimated using the method implemented in the *adehabitatHR* package (Calenge, 2006).

3.2 Environmental Covariates

3.2.1 Land Cover

The Earth Observation for Sustainable Forests' (EOSD) land cover classification map (Wulder and Nelson, 2003) was used as a habitat map and was updated each year of the study period with natural and anthropogenic disturbance data from digital forest inventory maps (Inventaire écoforestier du Québec) produced by the Ministère des Forêts, de la Faune et des Parcs (MFFP).

The EOSD land cover classification map, produced in 2002 by the Canadian Forest Service using Landsat imagery, was used as a baseline of available habitats at the beginning of the study period. Habitat classes were further aggregated based on ecological attributes previously shown to be relevant to woodland caribou during calving (ECCC, 2020; Rudolph et al., 2012). A detailed list of EOSD land cover classes and the corresponding habitats classes used for subsequent analyses in this study is available in *Supplementary Table 2*.

Digital maps from Québec's 3rd (MRNF, 2009), 4th (MFFP, 2015), and 5th (MFFP, 2021) forest inventories were utilised to characterise habitat disturbances that occurred within the Waswanipi region during the study period. Forestry-related disturbance polygons were classified as "cutblocks" while natural disturbance polygons were classified as "burns". A complete list of forest inventory disturbance classes and the corresponding disturbance classes used in this study is available in *Supplementary Table 3*.

Using the year each disturbance occurred, "cutblocks" and "burns" were further classified into "recent" (0 to 5 years old) and "old" (6 to 50 years old) to produce annual categorical maps for each year of the study period (2004 to 2020). An automated change detection algorithm based on satellite imagery was used to validate the year of disturbance associated with each polygon in the MFFP's forest inventory maps. Satellite images captured during calving season by medium resolution (30-metre) sensors from the Landsat 5, 7, and 8 (EROS, 2018a, 2018b) missions were used to build a time series of Normalised Burn Ratio (NBR) from 1984 to 2020. The LandTrendr change detection algorithm (Kennedy et al., 2018, 2010) was then used to detect the years when significant drops in NBR, indicating a forest disturbance, were observed in each 30-metre pixel of the study area. Within each disturbance polygon, the disturbance year that was most frequently detected (*i.e.* mode) by the LandTrendr algorithm was recorded and subsequently compared to the year recorded in the forest inventory. In case of a disagreement between both years, the earliest year was selected. One exception was if LandTrendr detected a change one year after the year recorded in the forest inventory map, which would suggest that the disturbance occurred after the calving season. In this situation, the year detected by LandTrendr was retained for subsequent analyses. All satellite imagery data was accessed with and remote sensing analyses were conducted in Google Earth Engine (Gorelick et al., 2017) using the JavaScript API.

Finally, a categorical land cover raster map incorporating habitat classes and disturbances was produced for each study year. The raster map of habitat classes based on the EOSD land cover classification map (circa 2002) was updated each year (2004 to 2020 inclusively) with the disturbances that occurred up to and during the current study year's calving season.

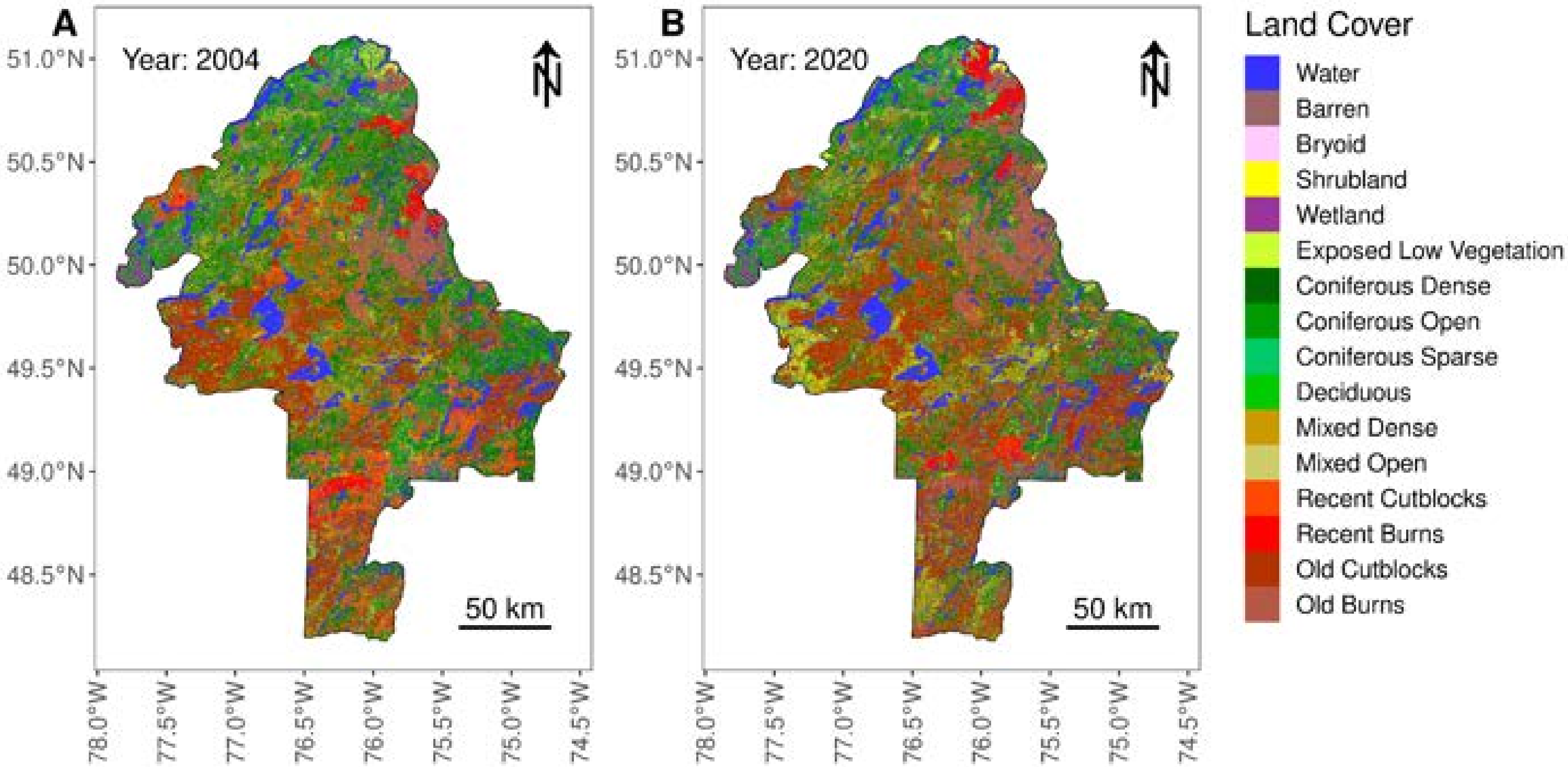

Figure 2. Map of land cover in the Waswanipi region at (A) the beginning (2004) and at (B) the end (2020) of the study period. Habitat classes are based on EOSD land cover classifications while natural and anthropogenic disturbances (burns and cutblocks) are based on MFFP forest inventories.

3.2.2 Road Density

Maps of road density within the Waswanipi region were produced for each study year using the road network spatial database available via the AQréseau product (MERN, 2021). The year of construction of each road was pinpointed by using a change detection algorithm based on Landsat imagery. Using the LandTrendr algorithm as detailed above, a time-series of NBR derived from images captured by Landsat 5, 7, and 8 sensors during calving season was examined to detect significant changes to forests in areas adjacent to roads. For each road polyline in AQréseau's database, the year of construction was assumed to be the earliest year of disturbance detected by LandTrendr in all the 30-metre pixels within a 60-metre buffer around that road. All satellite imagery data was accessed with and remote sensing analyses were conducted in Google Earth Engine (Gorelick et al., 2017) using the JavaScript API.

Previous studies investigating the spatial scales of habitat selection in Quebec have shown that calving woodland caribou avoid areas within 8 kilometres of roads (Leblond et al., 2011). To capture the effects of roads at a similar landscape scale, density raster maps were produced by computing, for each 500-metre cell, the density of all roads and railways (*e.g.* logging, municipal, provincial, federal) contained within an 8-kilometre radius from the cell's centre. Road density maps were recomputed every year of the study (2004 to 2020 inclusively) to incorporate new roads built since the previous study year's calving season. All road density raster maps were produced using R (R Development Core Team, 2020).

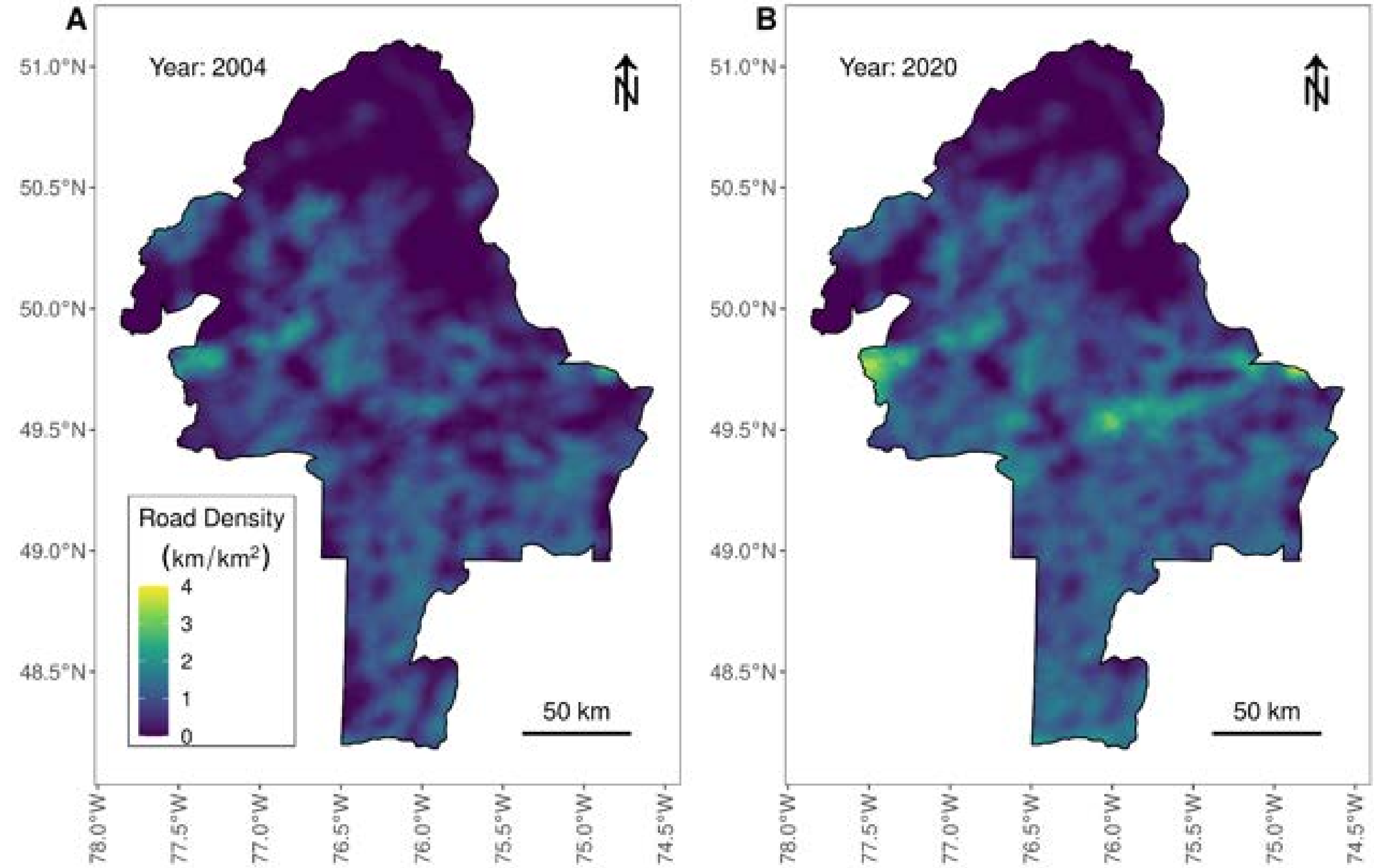

Figure 3. Maps of road density (km/km^2) in the Waswanipi region. Each panel illustrates road density (A) in 2004 and (B) in 2020 to highlight increased road density during the study period. Road density was derived from road network data available from the AQréseau database (MERN, 2021).

3.2.3 Distance to Water

A single raster map of the distance to the nearest water body was produced for the Waswanipi region during the study period. Woodland caribou are known to select calving habitats adjacent to water bodies, such as islands and peninsulas (ECCC, 2020). The 30-metre resolution raster map of distance to water was produced by computing the Euclidean distance to the nearest water pixel found in the EOSD land cover classification map. The distance to water map was assumed to remain unchanged throughout the study period and was produced using R (R Development Core Team, 2020).

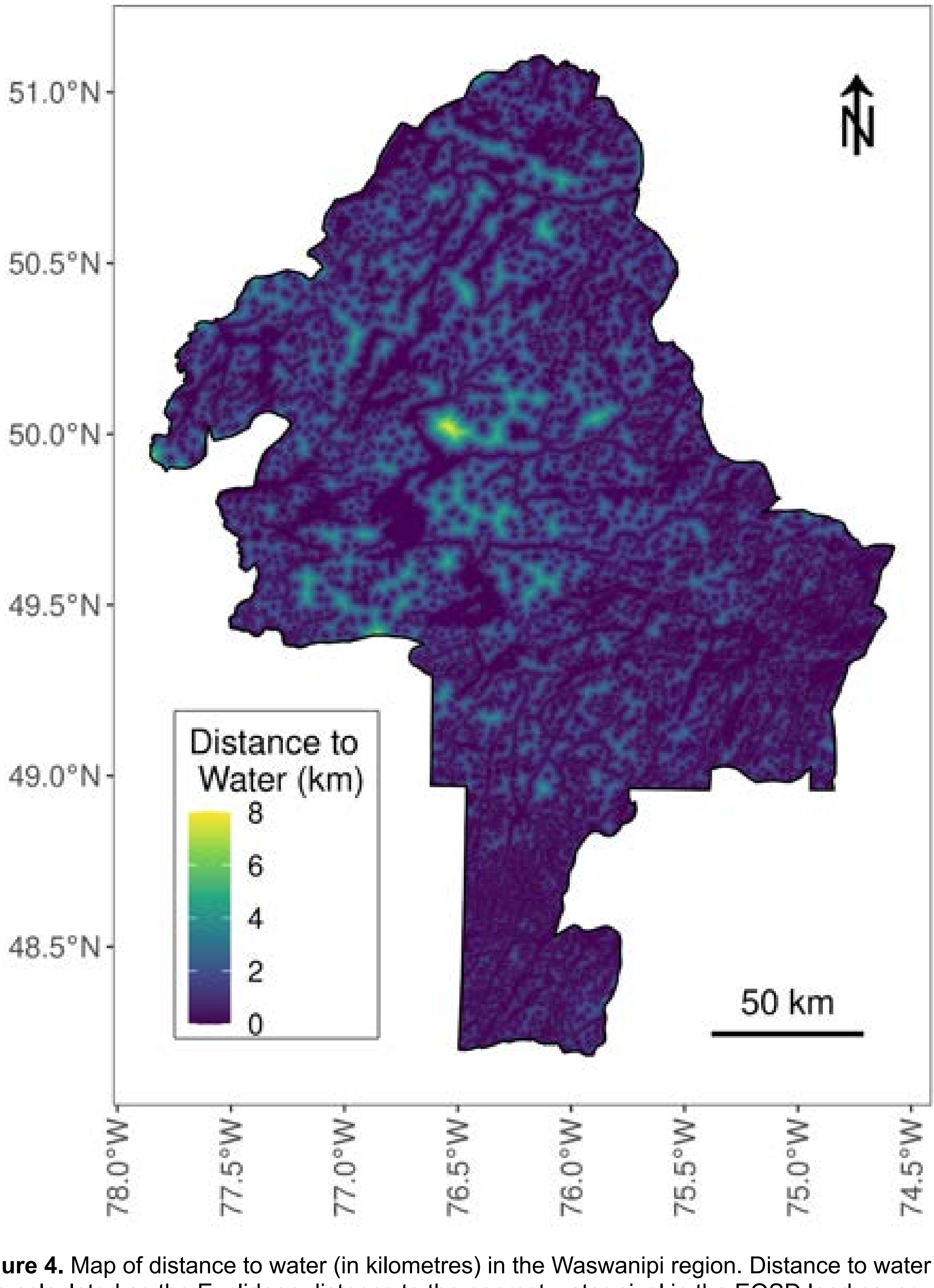

Figure 4. Map of distance to water (in kilometres) in the Waswanipi region. Distance to water was calculated as the Euclidean distance to the nearest water pixel in the EOSD land cover map (see Figure 2) and was assumed to be constant throughout the study period.

3.3 Calving Habitat Selection

3.3.1 Sampling Habitat Use-Availability

For each distinct calving event identified in *Section 3.1*, land cover classes, road density, and distance to water maps were sampled in used (*i.e.* observed) and available (*i.e.* random) locations. Available locations associated with a given calving event were randomly sampled in terrestrial habitats within a 51-kilometre buffer of the given calving range, excluding areas outside the Waswanipi region. To capture the breadth of possible calving ranges to select at the spatial scale of caribou movement, the buffer distance was calculated as the mean total distance that calving females travelled during spring, calving, and post-calving seasons. For each used location within a calving range, 100 corresponding available locations were randomly sampled in the surrounding buffer (see Figure 5). Rapid forestry-related landscape change during the study period was accounted for by sampling environmental covariates from annually updated maps reflecting the cumulative changes that occurred in prior years up to the calving season of the year a given calving event took place.

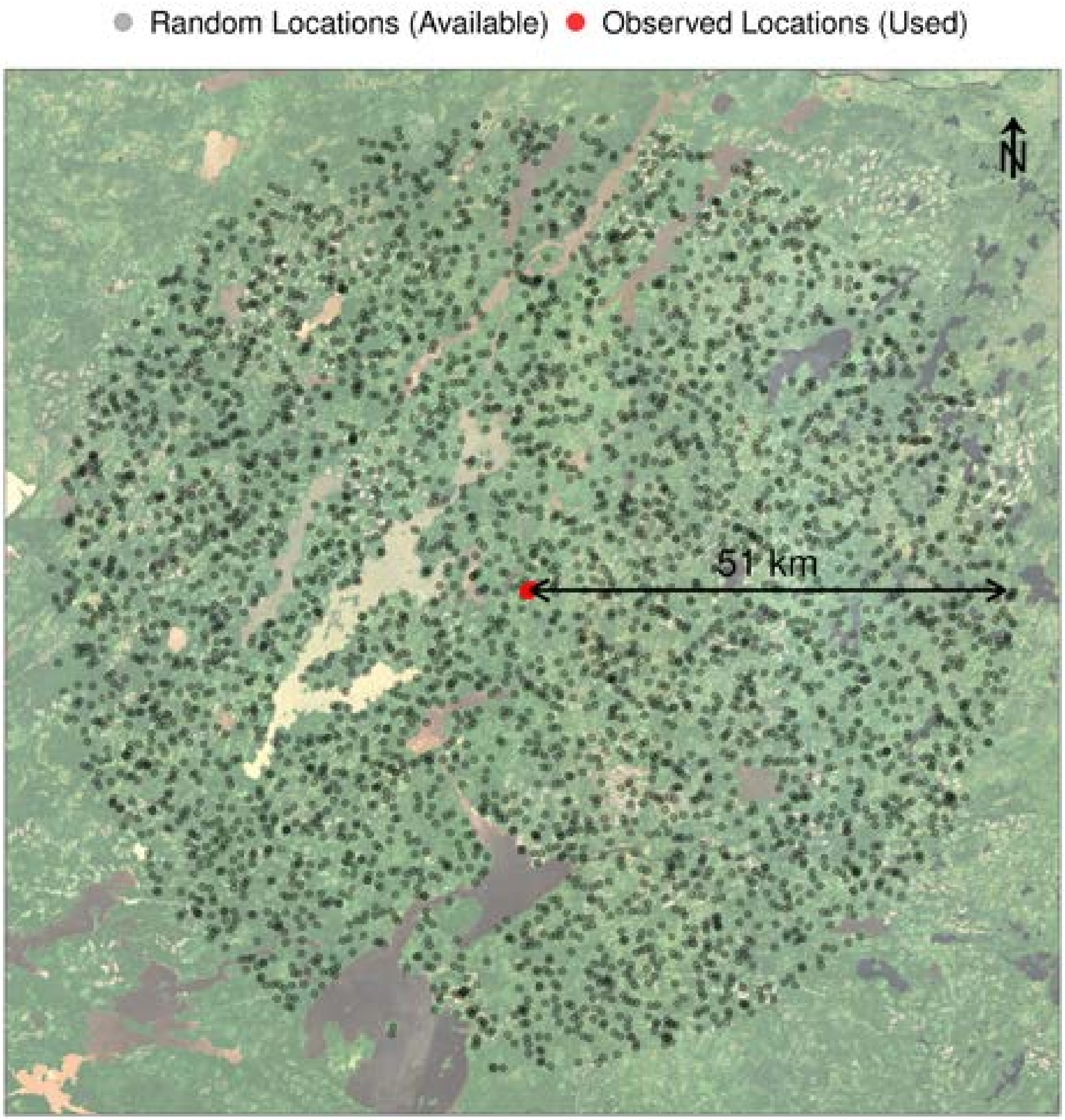

Figure 5. Example of the random sampling strategy employed to estimate Manly's global selection ratios and resource selection functions. Red points represent the observed locations ("used") of a fictitious female during calving. Black points represent random locations ("available") in the surrounding landscape. Random locations were sampled from terrestrial habitats in Waswanipi within a 51-kilometre radius of each female's calving range. Basemap is a Sentinel-2 RGB annual composite.

3.3.2 Selection Ratio

Selection or avoidance of each habitat was evaluated by computing Manly's global selection ratio (Manly et al., 2004) across all calving events. Specifically, this is calculated as the ratio of the proportion of use of a given habitat to that habitat's relative prevalence in the available landscape across all calving events. A ratio of 1 thus indicates that a given habitat is used as frequently as it is found in the landscape, while above or below a ratio of 1 suggests selection and avoidance, respectively. Selection ratios were computed using the *widesIII* function in the *adehabitatHR* package (Calenge, 2006) implemented in R (R Development Core Team, 2020).

3.3.3 Resource Selection Function

Probability of habitat use by female caribou during calving season was modelled using a resource selection function (RSF) fit with a hierarchical (*i.e.* mixed-effects) logistic regression. Using a use-availability design (Johnson et al., 2006), the RSF was fit assuming the exponential form:

$$\omega(x) = exp\left(\beta_0 + x_1\beta_{1ij} + \ ... \ + x_k\beta_{kij} + \gamma_{kj}x_{kj} + \gamma_{0j}\right)$$

where $x_1 ... x_k$ are environmental covariates; β_0 is the population level intercept; $\beta_1 ... \beta_k$ are coefficients to be estimated; and γ_{kj} and γ_{0j} are the random coefficients fitted to environmental covariate x_k and the random intercept within group *j* (Gillies et al., 2006). Based on environmental covariates previously identified as important to selection of calving habitats (ECCC, 2020), three explanatory variables were included in the model: (i) annually updated land cover (categorical variable), (ii) annually updated road density (continuous variable), and (iii) distance to water (continuous variable). Land cover classified as “Water” and “Exposed Low Vegetation” were removed prior to modelling because they were not usable calving habitats or were too rare for meaningful inference. Since use-availability observations associated with each calving event are not independent observations, observations for each calving event were grouped using a factor accounting for “individual-year” and included as a random effect in the model, effectively allowing the coefficients to vary within each group.

Because habitat availability is only an estimation of the true composition of the surrounding landscape, the hierarchical logistic regression was fit using an arbitrarily large weight of 5000 for “available” locations and a weight of 1 for “used” locations (Fithian and Hastie, 2013). To further ensure the interpretability and stability (*i.e.* reproducibility) of model coefficients, 100 available locations were included in the model for each used location (Fieberg et al., 2021; Warton and Shepherd, 2010). Selection or avoidance of habitat covariates was estimated using relative selection strength (RSS; Avgar et al., 2017) using “Open Coniferous Forest” as a reference level. Coefficients for the hierarchical logistic regression were estimated using the *lme4* package (Bates et al., 2015) implemented in R (R Development Core Team, 2020).

To monitor potential calving habitats over the course of the study period, RSF maps were created to inspect probability of use in Waswanipi between 2004 and 2010. Using the raster maps of environmental covariates for each year as inputs, the fitted RSF model was used to produce annual maps of the predicted probability of use as calving habitat. The predicted probability of use for each habitat pixel was pooled across all years and separated into 10 equal-interval bins (Morris et al., 2016). The equal-interval bins were then used to classify each annual habitat map into 10 classes ranging from “low” to “high” probability of use for calving. Proportions of habitats in each probability of use class were then computed to monitor declines in potential calving habitats during the study period. All modelling, statistics, and spatial analyses were computed in R (R Development Core Team, 2020).

4. Results

4.1 Calving Ranges

The inspection of GPS location time series helped identify 55 distinct calving events by 19 female woodland caribou in Waswanipi between 2004 and 2020. The majority of calving ranges were located in the region northwest and north of the community of Waswanipi (see Figure 6) in undisturbed coniferous forests with low road density. With the exception of 2013 and 2014, calving events were identified every year of the study period (see Figure 6). Between 1 to 5 calving events were typically identified for each female included in this study, though 1 female did display typical calving movement behaviours for 8 seasons (see Suppl. Table 1). During confirmed calving events, most collars collected GPS fixes approximately every 8 to 12 hours, and the total GPS locations collected during each distinct event typically varied from 20 to 50 recorded locations (see Suppl. Table 1). Calving females were predominantly from the Assinica herd, though one individual was from the Nottaway and another had no assigned herd (see Suppl. Table 1).

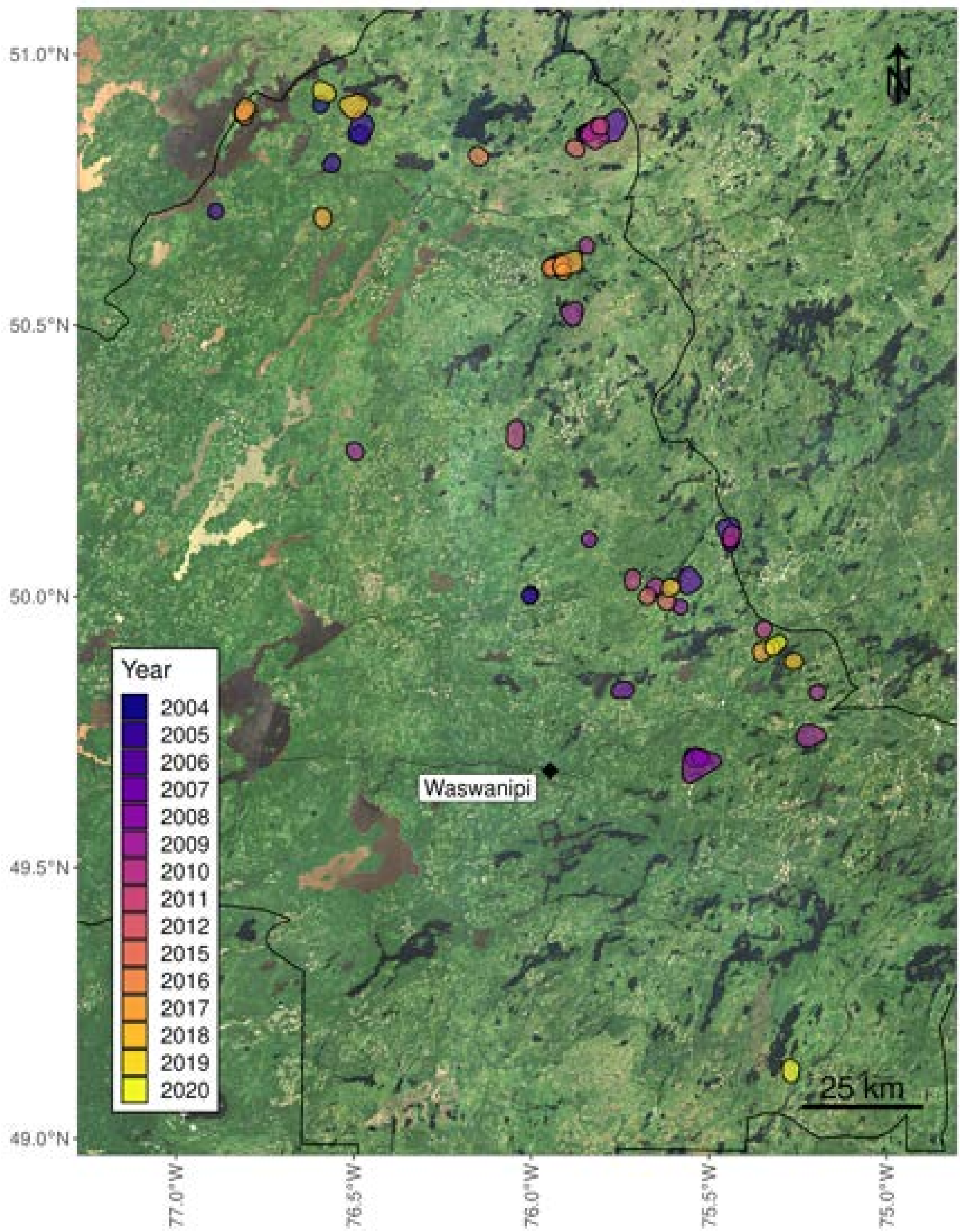

Figure 6. Map of 55 calving ranges used by 19 female woodland caribou within the Waswanipi region between 2004 and 2020, inclusively. Calving ranges were estimated using a minimum convex polygon (MCP) encompassing 95% of relocations collected via GPS-fitted collars during calving events. An additional buffer of 1500 metres was added to MCPs to facilitate visualisation. Basemap is a Sentinel-2 RGB annual median composite.

4.2 Calving Habitat Selection

4.2.1 Habitat Composition and Selection Ratios

Amongst the undisturbed habitats available throughout the study period in the Waswanipi region, calving woodland caribou typically selected coniferous forest habitats. Open coniferous forest habitats were especially prized by calving females. While they only covered 25.8% of potentially available habitats, 48.5% of all locations recorded during calving were observed in open coniferous forest (see Figure 7a). Manly's selection ratio for open coniferous forest habitats was 1.7 and statistically significant, indicating that this habitat was used at almost double the rate of its relative availability in the landscapes surrounding calving ranges. Sparse and dense coniferous habitats were also heavily utilised during calving, together accounting for 23.8% of habitats used during calving while only representing 16.7% of all available habitats. Wetlands, open mixed forests, and dense mixed forests account for most of the remaining habitat use (24.1%) during calving, though they are each used at approximately the same rate as they are available as demonstrated by selection ratios of around 1 (see Figure 7b). Barren, shrubland, deciduous forests, and exposed low vegetation habitats, though uncommon, were nonetheless avoided by females during calving season (see Figure 7).

All disturbed habitats available throughout the study period were strongly avoided by calving females. Selection ratios for recent and old cutblocks were both 0 (see Figure 7b), showing strong avoidance of forestry impacted areas. Together these areas accounted for 11.2% of available habitats and only 0.1% of used habitats (see Figure 7a). Recent burns and old burns were more abundant, accounting for 4.5% and 14.5% of available habitats, respectively. While selection ratios for burns demonstrated strong avoidance, old burn habitats were nonetheless used most frequently amongst disturbed habitats, with 3.8% of locations observed in old burns during calving.

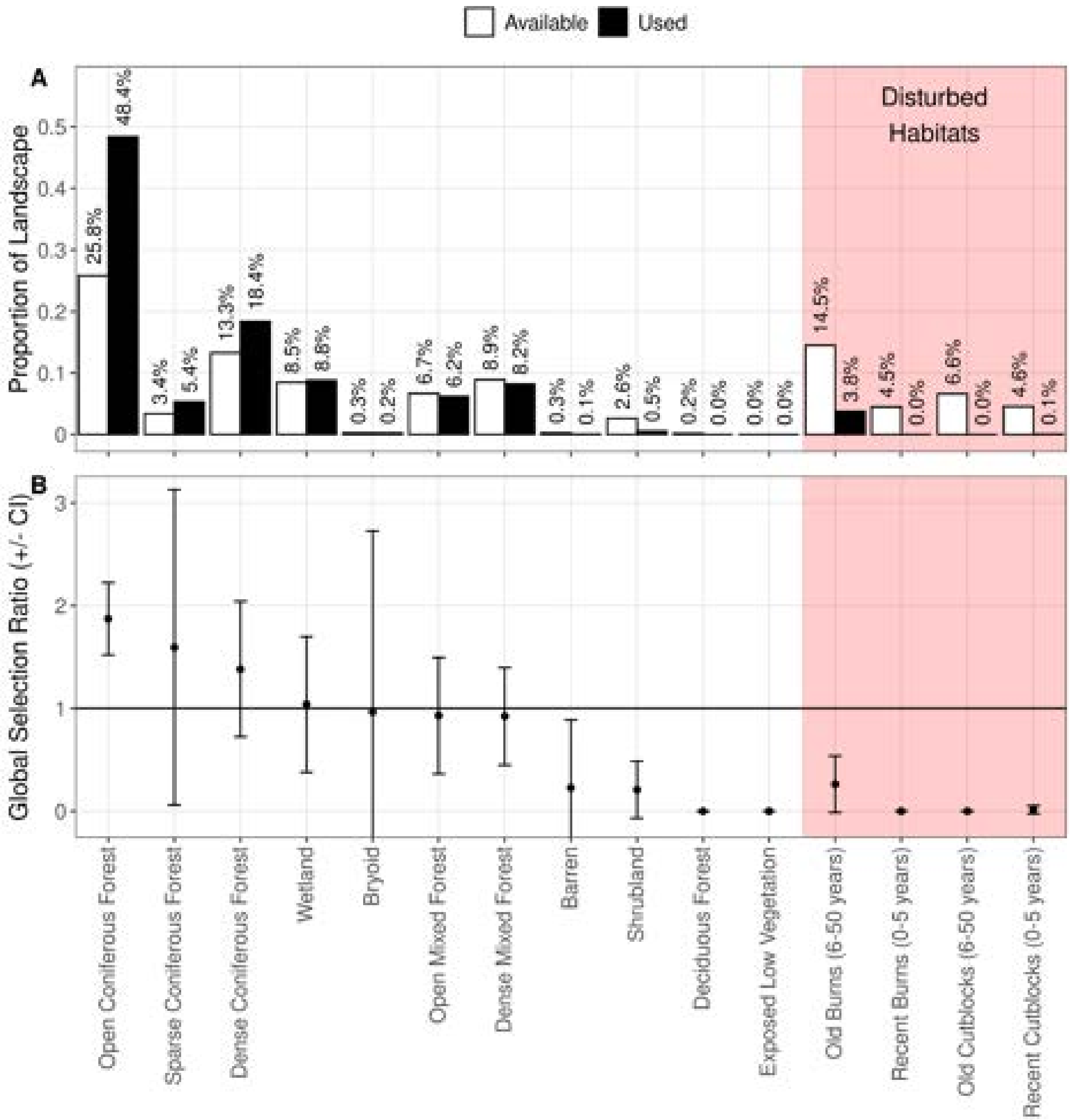

Figure 7. Use, availability, and selection-avoidance of land cover classes across all calving events in the Waswanipi region between 2004 and 2020. (A) Proportion of used (*i.e.* observed) and available (*i.e.* random) land cover classes are presented with distinction between undisturbed habitats (in white) and disturbed habitats (in red). (B) Selection or avoidance of each habitat class is indicated by Manly's global selection ratios (± 95% confidence intervals), where statistically significant selection or avoidance correspond to ratios with confidence intervals entirely above or below 1, respectively.

4.2.2 Selection of Land Cover Classes

All the natural (*i.e.* undisturbed) habitats included in the land cover classification had statistically significant effects on calving habitat selection by female woodland caribou in Waswanipi between 2004 and 2020 (see Figure 8 & Suppl. Table 4). Open coniferous forest, the habitat most prized by calving females, was used as a reference level to assess the relative selection strength (RSS) of other habitat covariates. RSS values indicate that, after open coniferous forests, calving females preferred sparse and dense coniferous forests, open and dense mixed forests, and wetlands (see Figure 8). The RSS values for these habitats ranged from 0.3366 to 0.1665 (see Suppl. Table 4), indicating that they were selected by calving females roughly 3 to 6 times less frequently than open coniferous forests. Other undisturbed habitats, such as shrublands, deciduous forests, and barren habitats were selected approximately 100 times less frequently than open coniferous forest (see Figure 8), with RSS values of 0.0251, 0.0121, and 0.0052, respectively.

All the disturbed habitats included in the land cover classification were significantly avoided by calving female woodland caribou in Waswanipi between 2004 and 2020 (see Figure 8 & Suppl. Table 4). Relative to open coniferous, both recent and old cutblocks were more than 1000 times less likely to be used by calving females, with RSS values of 0.0006 and 0.0008, respectively (see Suppl. Table 4). Burns were also avoided during calving, though old burns were avoided at a lesser rate than recent burns, with RSS values of 0.0123 and 0.0005, respectively (see Suppl. Table 4).

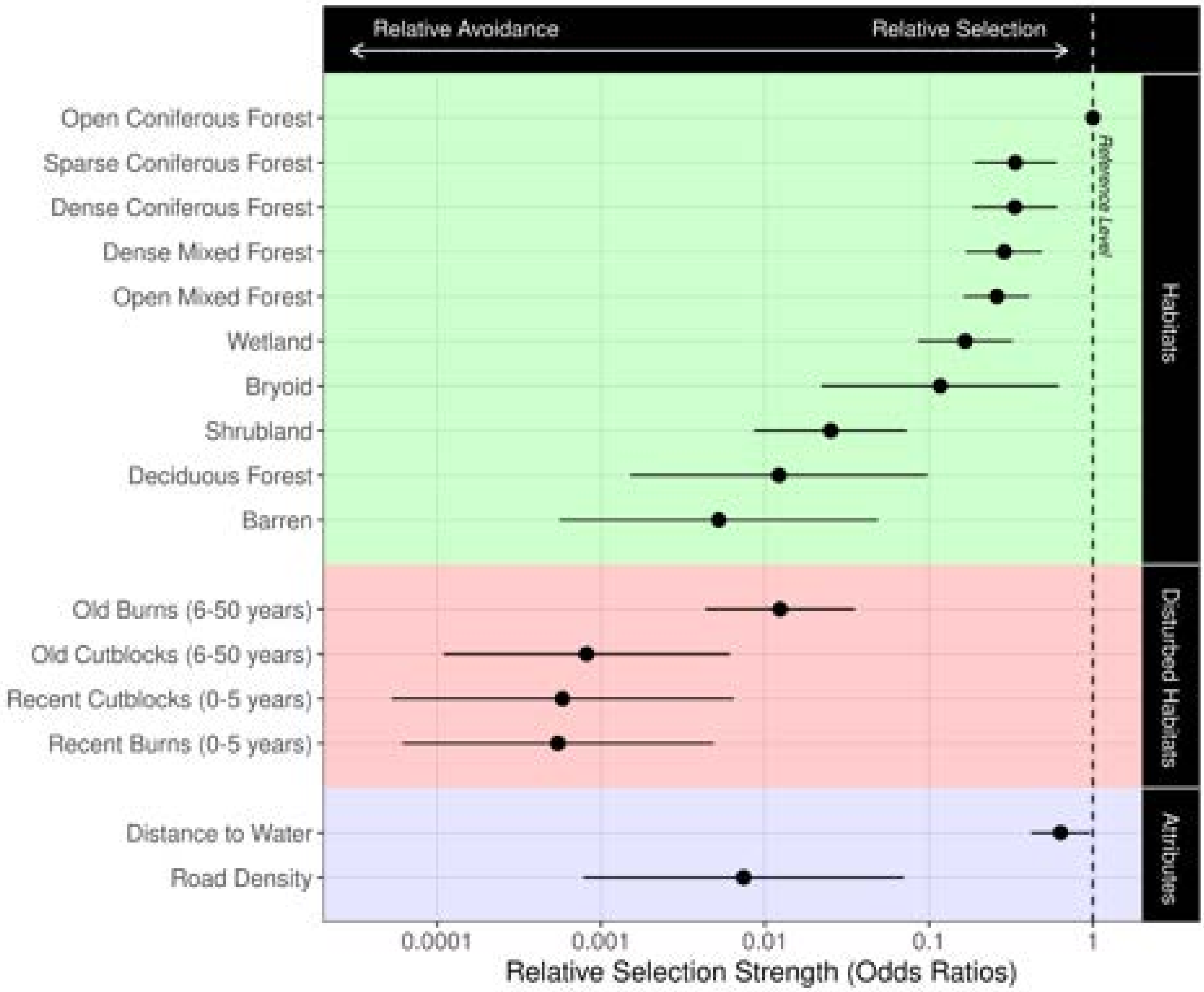

Figure 8. Selection or avoidance of habitats by female woodland caribou during calving season in Waswanipi between 2004 and 2020. Relative selection strength (± 95% confidence intervals) was estimated with the resource selection function described in *Section 3.3.3*, and describes selection or avoidance relative to the "Open Coniferous Forest" reference level. Land cover classes are presented as "Habitats" (in green) and "Disturbed Habitats" (in red), while the two continuous environmental covariates are presented as "Attributes" (in blue). All variables were statistically significant (see Suppl. Table 4).

4.2.3 Road Density and Distance to Water

Both continuous environmental covariates had significant effects on calving habitat selection by female woodland caribou over the course of the study period.

Habitats with high road density were avoided by calving females (β = -4.9066, *P*-value = 0.00002; see Figure 8 and Suppl. Table 4). Female woodland caribou almost exclusively selected calving habitats in areas where road density was less than 0.5 km/km2. All else being constant, the RSF predicted that in habitats where road density was higher than 0.5 km/km2, the relative probability of use dropped to 0 (see Figure 9A).

In contrast, calving females showed slight preference for habitats close to water bodies (β = -0.4534, *P*-value = 0.03211; see Figure 8 and Suppl. Table 4). All else being constant, the RSF predicted a very gradual increase in relative probability of use when habitats were closer to water, with probability of use almost doubling in habitats adjacent to water relative to habitats 4 km away (see Figure 9B).

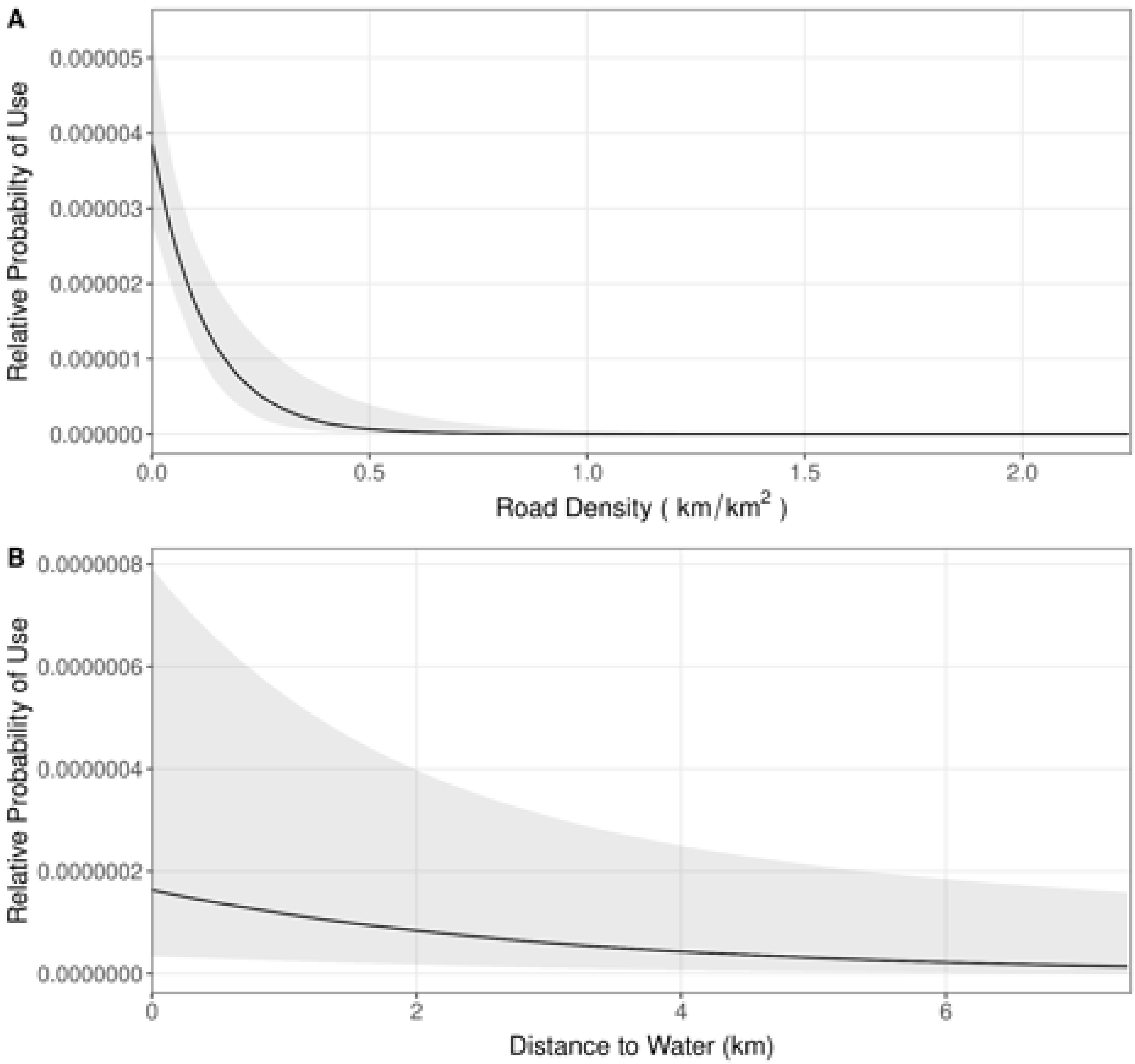

Figure 9. Effects of (A) road density (km/km^2) and (B) distance to water (km) on the relative probability of use as calving habitat by woodland caribou in Waswanipi between 2004 and 2020. The solid line depicts the relative probability of use predicted by the resource selection function (RSF) described in *Section 3.3.3*, while the grey shading depicts the 95% confidence intervals. RSF predictions for a single continuous variable are estimated while holding all other variables constant.

4.3 Decline of Calving Habitats

The availability of potential calving habitats identified through habitat selection analyses within the Waswanipi region has undergone steady declines between 2004 and 2020 (see Figure 10 & Suppl. Figures 1 to 17).

The overall proportion of habitats suitable for calving within Waswanipi has steadily declined between 2004 and 2020 (see Figure 10C). Habitats classified as having the lowest probability of use for calving (the lowest equal-interval bin amongst 10 bins) occupied just over 85% of Waswanipi's territory in 2004. This proportion increased to 92% by 2020. Habitats ranked in the top 5 (of 10) equal-interval bins with the highest probability of use for calving occupied 3.4% of Waswanipi's landscape in 2004. However, these high quality calving habitats only occupied 1.9% of Waswanipi's landscape by the year 2020 (see Figure 10C), representing a 45% loss. Habitats classified as having the highest probability of use for calving (the highest equal-interval bin amongst 10 bins), occupied 0.35% of the landscape in 2004, but only 0.23% by 2020, a loss of 33% over the course of the study period.

At the beginning of the study period, there were small relatively undisturbed areas immediately south as well as east of the Waswanipi community where probability of use as calving habitat was higher, but these have disappeared following logging activity. In 2004, the areas surrounding Lac Matagami in the westernmost part of the Waswanipi region, were predicted to have a high probability of use as they were dominated by wetlands and open coniferous forests (see Figure 2). Following logging activity, notable declines in potential calving habitats occurred in the area north-east of Lac Matagami began around 2009 (see Suppl. Figures 5 to 12).

The most important calving habitats within Waswanipi are located in the northern part of the traditional territory where both natural and anthropogenic disturbances have had increasing impacts on the landscape between 2004 and 2020. Most calving ranges were located in the region east of Lac Evans, as well as the areas surrounding the Broadback river, especially between Lac Théodat and the Lac Salamandre and Lac Quénonisca areas (see Figure 6), which are all characterised by high quality calving habitats (see Figure 10). The areas west of Lac Assinica and Lac Comencho falling within the Waswanipi traditional territory were also identified as important calving habitats. Due to the prevalence of coniferous forest habitats (see Figure 2) and low road density in all these areas (see Figure 3), the RSF model predicted high probabilities of use by calving females. However, the most important declines in calving habitat quality during the study period occurred in these areas (see Figures 10A & 10B, Suppl. Figures 1 to 17). Specifically, the calving habitats south of the Broadback river around Lac Quénonisca and Lac Roger underwent important declines in the past 15 years following important expansion of logging roads and forestry activity in the area. The calving habitats west of Lac Assinica and Lac Comencho falling within the Waswanipi traditional territory have undergone important declines for the same reasons. The calving habitats north and east of Lac Théodat, however, underwent important declines following large forest fires. Additional maps illustrating these changes in greater detail are available in Supplementary Figures 1 to 17.

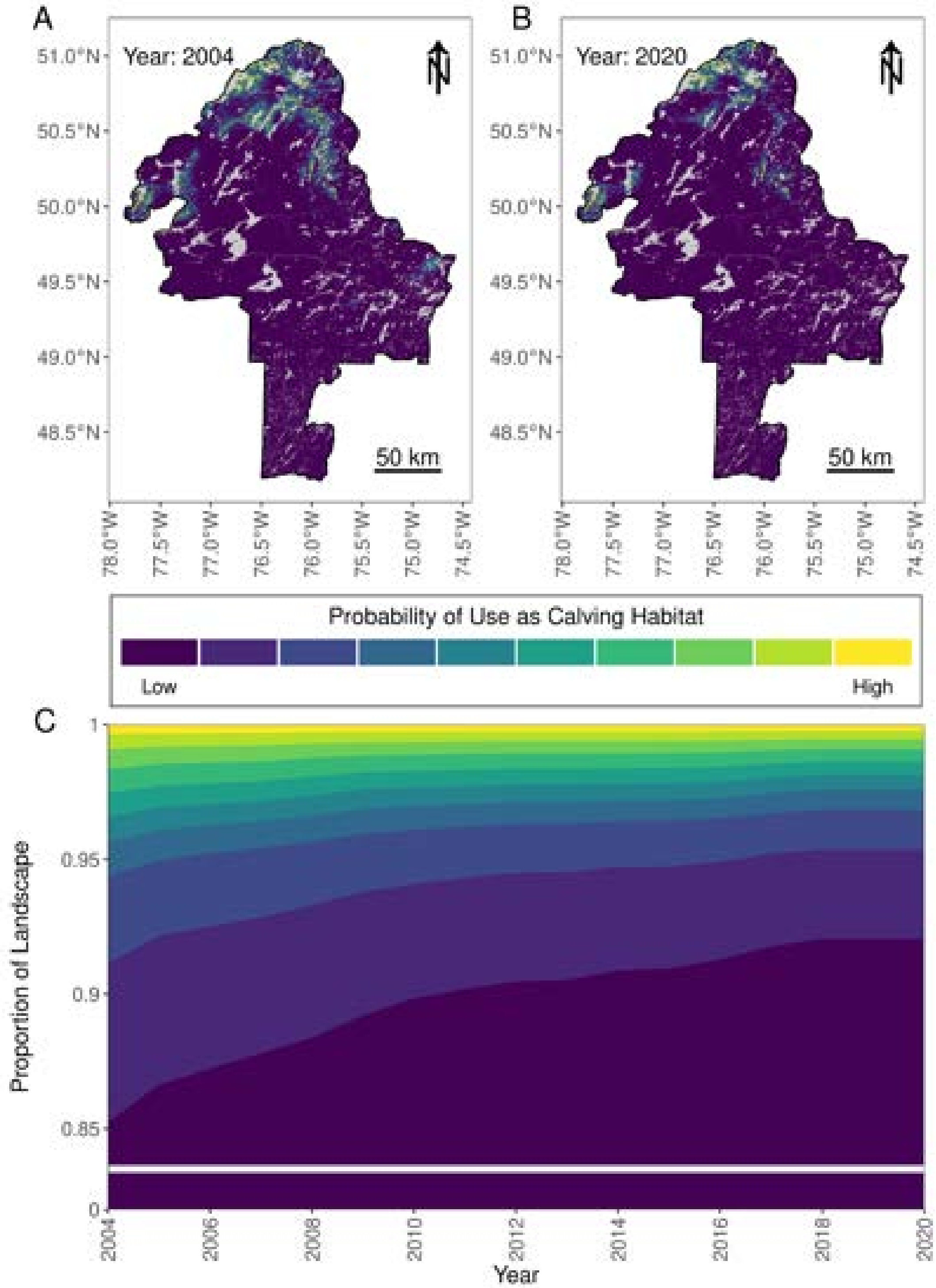

Figure 10. Probability of use as calving habitat in the Waswanipi region between 2004 and 2020. Maps display probability of use as calving habitat at (A) the beginning and (B) the end of the study period. (C) Time series of landscape composition shows proportion of all Waswanipi habitats within bins ranging from low to high probability of selection. Note the insertion of an axis break between 0 and 85% to maximise visualisation of bins with higher probability of use. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies are displayed in grey.

5. Recommendations

Because the productivity of boreal forests is relatively low, natural restoration of habitats to suitable caribou habitats can take several decades. The effects of disturbances that have occurred since 2004 are likely to persist for many years, and continued declines in calving habitats will undoubtedly have important effects on population health. Consequently, to prevent further degradation of woodland caribou calving habitats in the Waswanipi regions, this study proposes the following:

1) An immediate moratorium on anthropogenic disturbances, especially exploitation of coniferous forests, in the northern region of Waswanipi.

The calving habitats identified in the northern part of Waswanipi are critical to the Assinica herd. The areas around Lac Evans, Lac Théodat, and the Broadback River, are especially important habitats and have been previously identified as such by traditional land users (Cree Regional Authority, 2010). If logging must continue, it should be limited to areas with preexisting forestry impacts adjacent to existing logging roads and prioritise the protection of large intact areas of undisturbed habitat (Courtois et al., 2007). Any new logging of areas within 10 to 15 kilometres of current calving habitats will likely lead to extirpation of caribou from that area within the next two decades (Vors et al., 2007).

2) An immediate moratorium on construction of logging roads and other linear anthropogenic disturbances, especially in areas adjacent to calving habitats.

Numerous studies in Quebec and Canada have confirmed that increased predation pressures near logging roads (and other linear disturbances) are likely the most important factor in calving habitat selection and calf survival (Courtois et al., 2007; Fortin et al., 2017; James and Stuart-Smith, 2000; Pinard et al., 2012; Whittington et al., 2011). Road avoidance has been detected in movement and habitat selection behaviours up to distances of 8 to 10 kilometres (Leblond et al., 2011; Rudolph, 2011).

Protecting existing calving habitats requires, at a bare minimum, the halting of all new road construction within this range of distances.

3) The reclamation of logging roads within Waswanipi to hinder predator access to remote calving areas.

This approach was proposed as a recovery strategy by the Quebec government as early as 2008 (MRNF, 2008), but preliminary trials only began in Côte-Nord in 2017 (Pernot et al., 2020). It will take decades for natural succession to restore these linear disturbances. Reclamation of roads could accelerate this process, especially if efforts are targeted in areas adjacent to critical habitats in the Waswanipi territory.

4) A continued moratorium on all harvesting of woodland caribou.

A continued moratorium on caribou harvest by traditional land users of the CFNW will aid adult female survival and, consequently, promote population recruitment.

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7. Supplementary Materials

Supplementary Table 1. Female woodland caribou included in this study along with their respective assigned herds, year of confirmed calving events, and number of GPS observations collected during each calving event.

Herd	Caribou ID	Calving Event Year	GPS Observations
Assinica	[redacted]	2004	28
		2005	19
		2006	48
		2007	22
		2008	25
	[redacted]	2004	34
		2005	35
		2006	37
		2007	25
		2009	20
		2010	30
		2011	32
		2012	113
	[redacted]	2004	44
		2005	21
		2006	45
		2007	25
		2008	27
	[redacted]	2005	44
	[redacted]	2006	41
	[redacted]	2008	33
		2009	37
		2010	29
		2012	96
	[redacted]	2008	22
		2009	15
		2015	22
		2016	32
		2017	18
		2018	19
	[redacted]	2008	14
		2009	21
		2010	18
	[redacted]	2010	49
	[redacted]	2009	38
		2010	19

		2012	49
	[redacted]	2009	22
		2010	40
	[redacted]	2009	24
	[redacted]	2015	21
		2017	29
		2018	19
	[redacted]	2015	20
		2016	28
		2017	14
	[redacted]	2017	34
	[redacted]	2016	11
		2017	37
		2018	21
		2019	12
	[redacted]	2020	19
Nottaway	[redacted]	2004	30
		2005	57
Currently Unassigned	[redacted]	2020	26

Supplementary Table 2. Classification scheme used to classify EOSD landscape classes into corresponding caribou habitat classes used in this study. Additional information on EOSD landscape classes are detailed in Wulder and Nelson (2003).

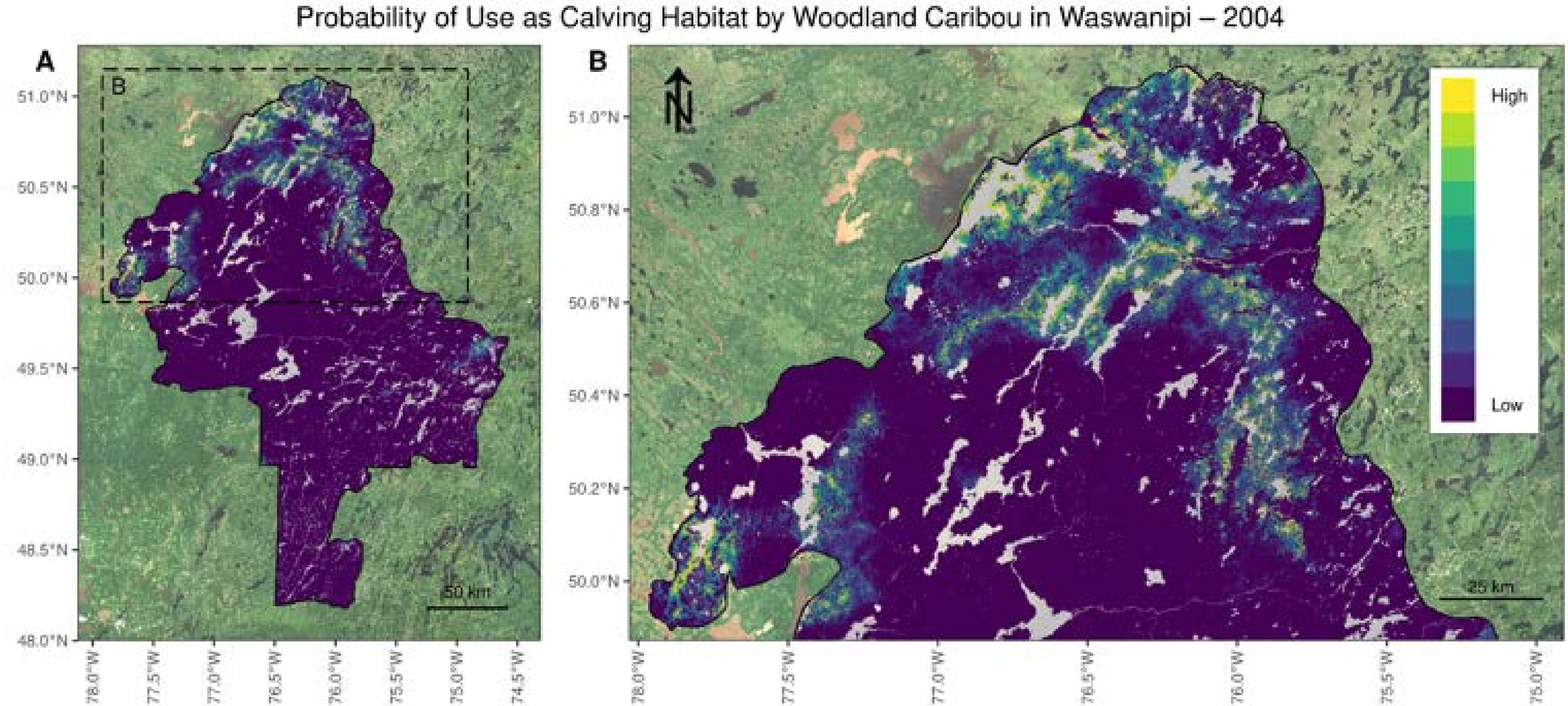
EOSD Codes	EOSD Landscape Classes	Habitat Classes
0	No Data	No Data
10	Unclassified	No Data
11	Cloud	No Data
12	Shadow	No Data
20	Water	Water
31 32 33 34	Snow/Ice Rock/Rubble Exposed / Barren Land Developed	Barren
40	Bryoids	Bryoid
51 52	Shrubland Tall Shrubland Low	Shrubland
81 82 83	Wetland-Treed Wetland-Shrub Wetland-Herb	Wetland
110 120	Grassland Agriculture	Exposed Low Vegetation
211	Coniferous Dense	Coniferous Dense
212	Coniferous Open	Coniferous Open
213	Coniferous Sparse	Coniferous Sparse
221 222 223	Broadleaf Dense Broadleaf Open Broadleaf Sparse	Deciduous
231	Mixedwood Dense	Mixed Dense
232	Mixedwood Open	Mixed Dense

Supplementary Table 3. Classification scheme used to classify disturbances from MFFP's forest inventory maps into the habitat disturbance categories used in the current study. Disturbance codes and corresponding database fields are presented for all three forest inventories used. Additional information on disturbance codes is available in MRNF (2009) and MFFP (2021, 2015).

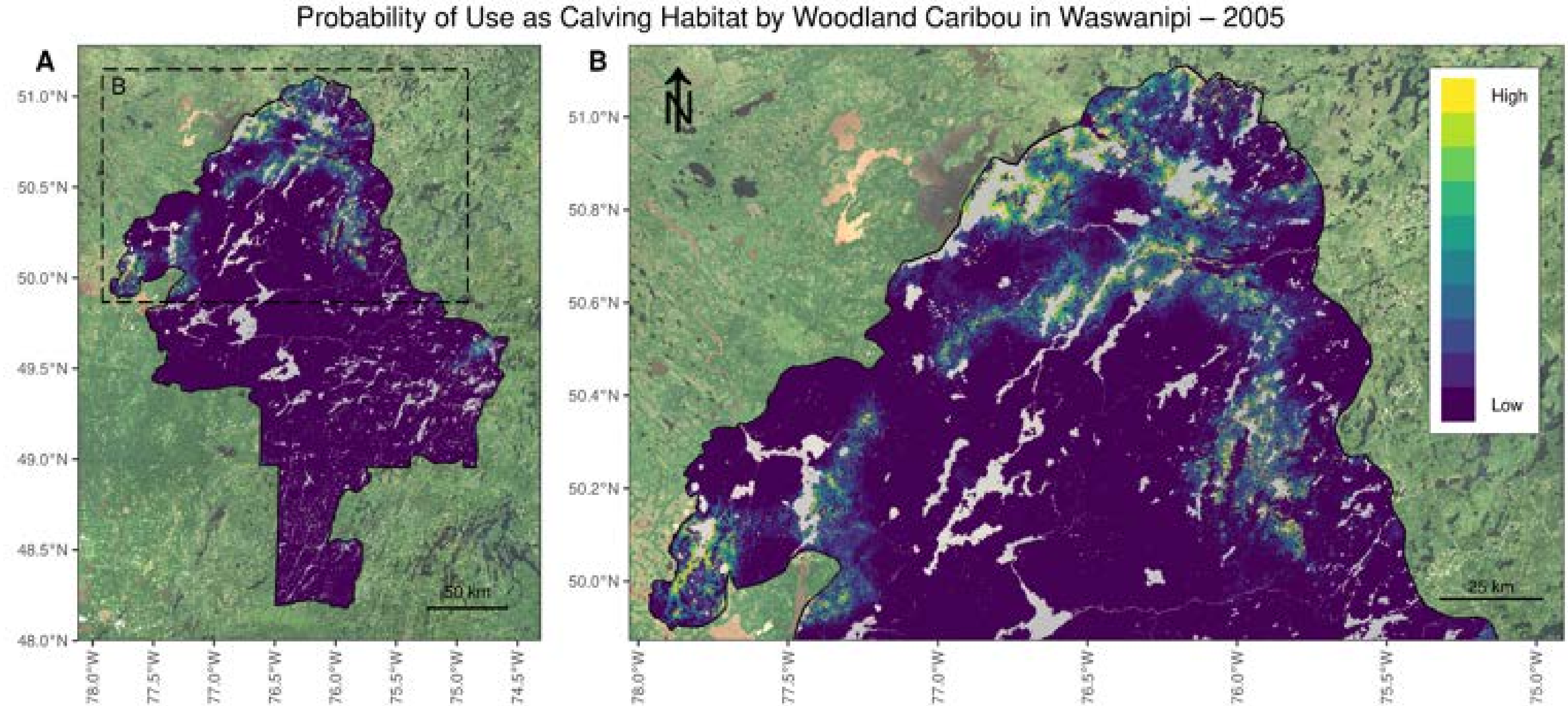
Inventory	Field (Description)	Disturbance Code	Habitat Disturbance
3rd	PER_CO_ORI (Severe disturbance)	BR, CHT, DT, ES, FR	Burns
		CBT, CPR, CT, ENM, ENS, P, PLN, PLR	Cutblocks
	PER_CO_MOY (Moderate disturbance)	CHP, BRP, EL	Burns
		CB, CP, EPC, DRM, DR	Cutblocks
4th	ORIGINE (Severe disturbance)	BR, ES, CHT, DT	Burns
		CT, PRR, CPR, P, RPS, CBA, REA, ENS, CEF, CRR, CPH, ETR, CPT, CRB	Cutblocks
	PERTURB (Moderate disturbance)	CHP, EL, DP, BRP	Burns
		CP, DEG, RR, RRG, EPC, EC, ECL, EPR, CPC, CA	Cutblocks
5th (MAJ)	ORIGINE (Severe disturbance)	BR, CHT, DT, ES	Burns
		CBA, CBT, CEF, CPH, CPHRS, CPI_RL_F, CPPTM_DIS, CPPTM_U, CPR, CPRS_BA, CPRS_U, CPT, CRB, CRR, CRS, CT, ENS, ETR, P, PL, PLR, PRR, REA, RPS	Cutblocks
	PERTURB (Moderate disturbance)	BRP, CHP, DP, EL	Burns
		CA, CP, CPC, CPI_CP, CPI_RL, CPI_TA, CPR_T, CPS, DEG, EC, ECL, ENP, EPC, EPC_SYS, NET, PL_REG, RPLB, RR, RRR	Cutblocks

Supplementary Table 4. Results from the hierarchical logistic regression used to fit the resource selection function (RSF). Coefficients (β), relative selection strength with 95% confidence levels, and significance levels (*P*-value) are presented for fixed-effect variables. Land cover classes are grouped into habitats and disturbed habitats, displayed in green and red, respectively. Environmental attributes are displayed in blue.

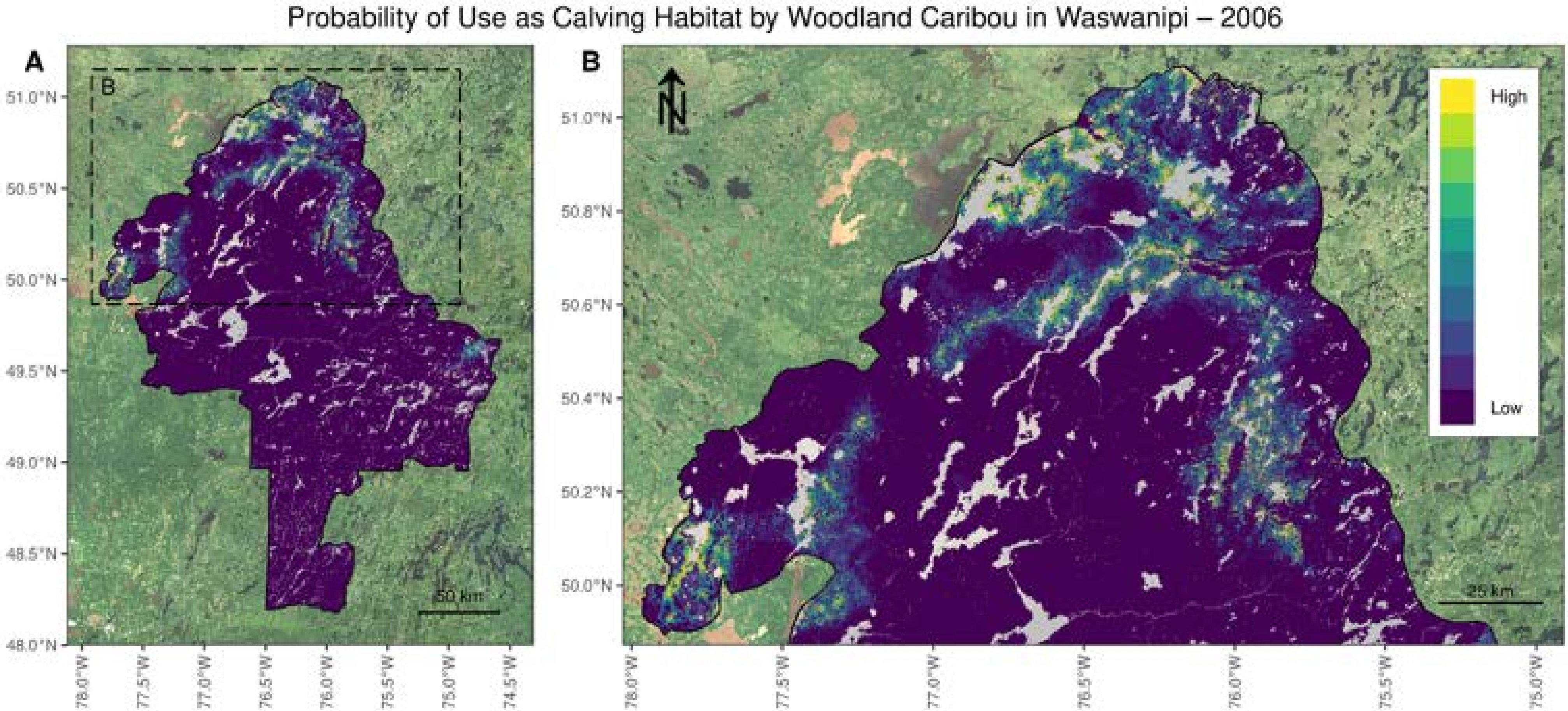
Fixed-Effect Variables	**Coefficient (β)**	**Relative Selection Strength (± 95% CI)**	**Significance *P(>|z|)***
Sparse Coniferous Forest	-1.0888	0.3366 (± 0.2949)	0.00022
Dense Coniferous Forest	-1.0946	0.3347 (± 0.3036)	0.00031
Dense Mixed Forest	-1.2448	0.2880 (± 0.2743)	<0.00001
Open Mixed Forest	-1.3490	0.2595 (± 0.2375)	<0.00001
Wetland	-1.7926	0.1665 (± 0.3397)	<0.00001
Bryoid	-2.1452	0.1170 (± 0.8501)	0.01162
Shrubland	-3.6842	0.0251 (± 0.5477)	<0.00001
Deciduous Forest	-4.4106	0.0121 (± 1.0648)	<0.00001
Barren	-5.2556	0.0052 (± 1.1423)	<0.00001
Old Burns (6-50 years)	-4.3956	0.0123 (± 0.5336)	<0.00001
Old Cutblocks (6-50 years)	-7.1121	0.0008 (± 1.0276)	<0.00001
Recent Cutblocks (0-5 years)	-7.4513	0.0006 (± 1.2251)	<0.00001
Recent Burns (0-5 years)	-7.5159	0.0005 (± 1.1168)	<0.00001
Distance to Water	-0.4534	0.6355 (± 0.2116)	0.03211
Road Density	-4.9066	0.0074 (± 1.1501)	0.00002



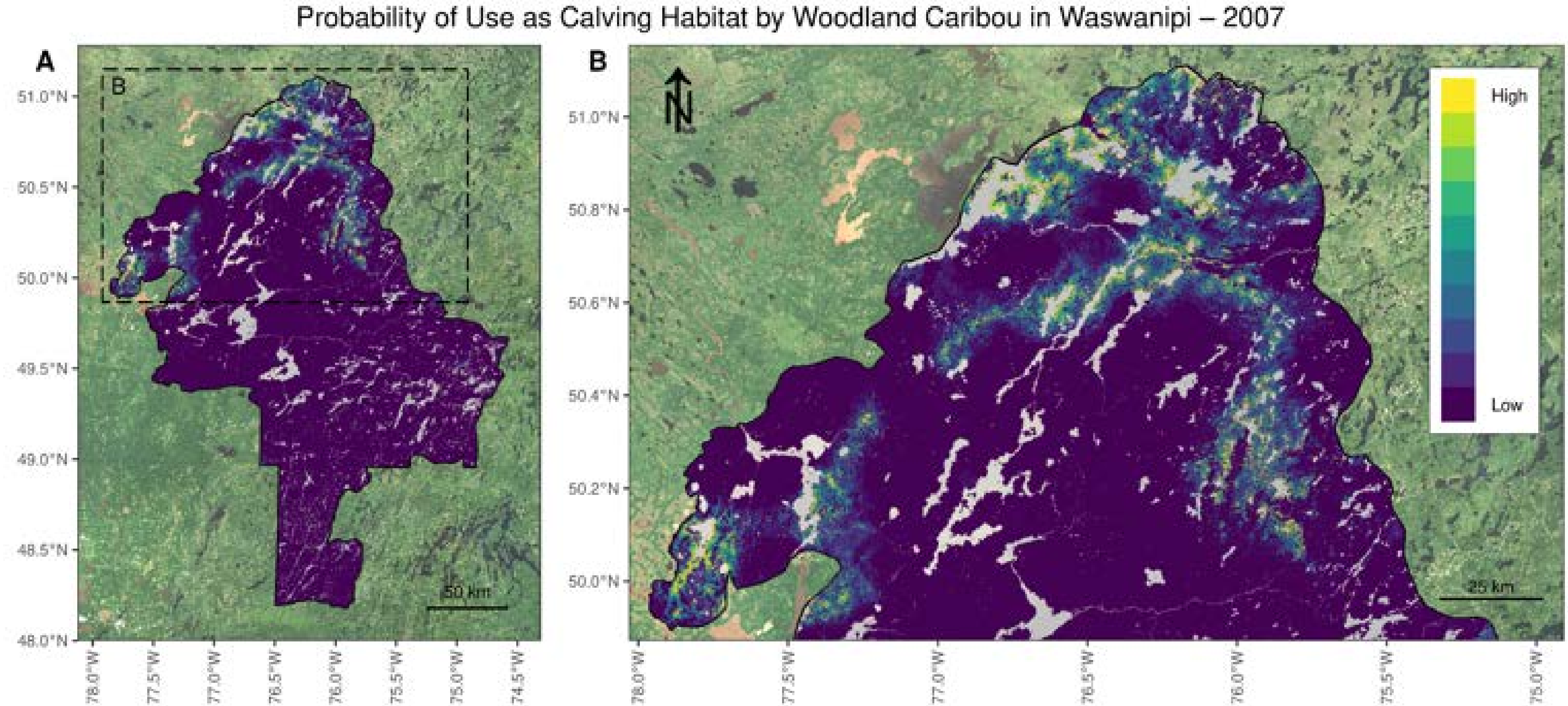
Supplementary Figure 1. Maps of probability of use as calving habitat in 2004 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



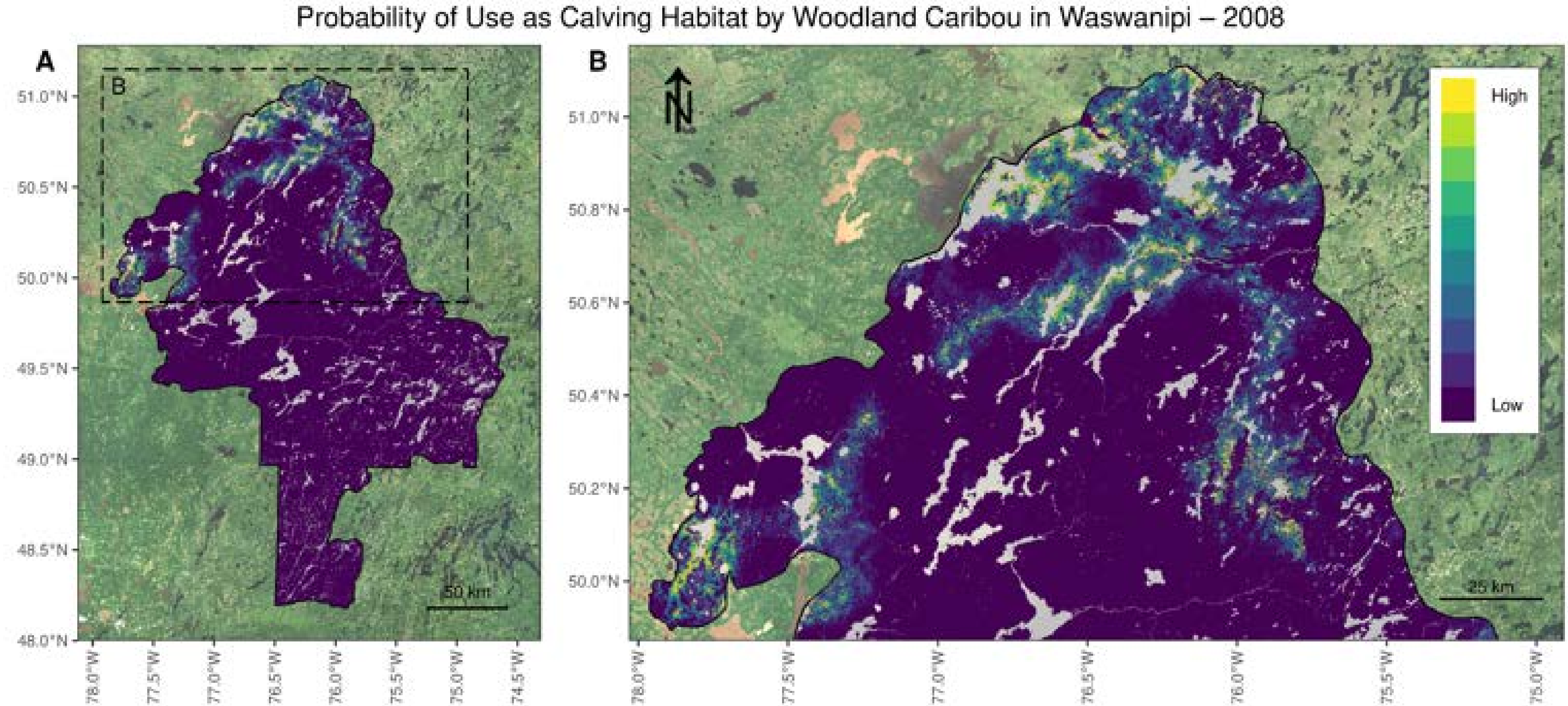
Supplementary Figure 2. Maps of probability of use as calving habitat in 2005 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



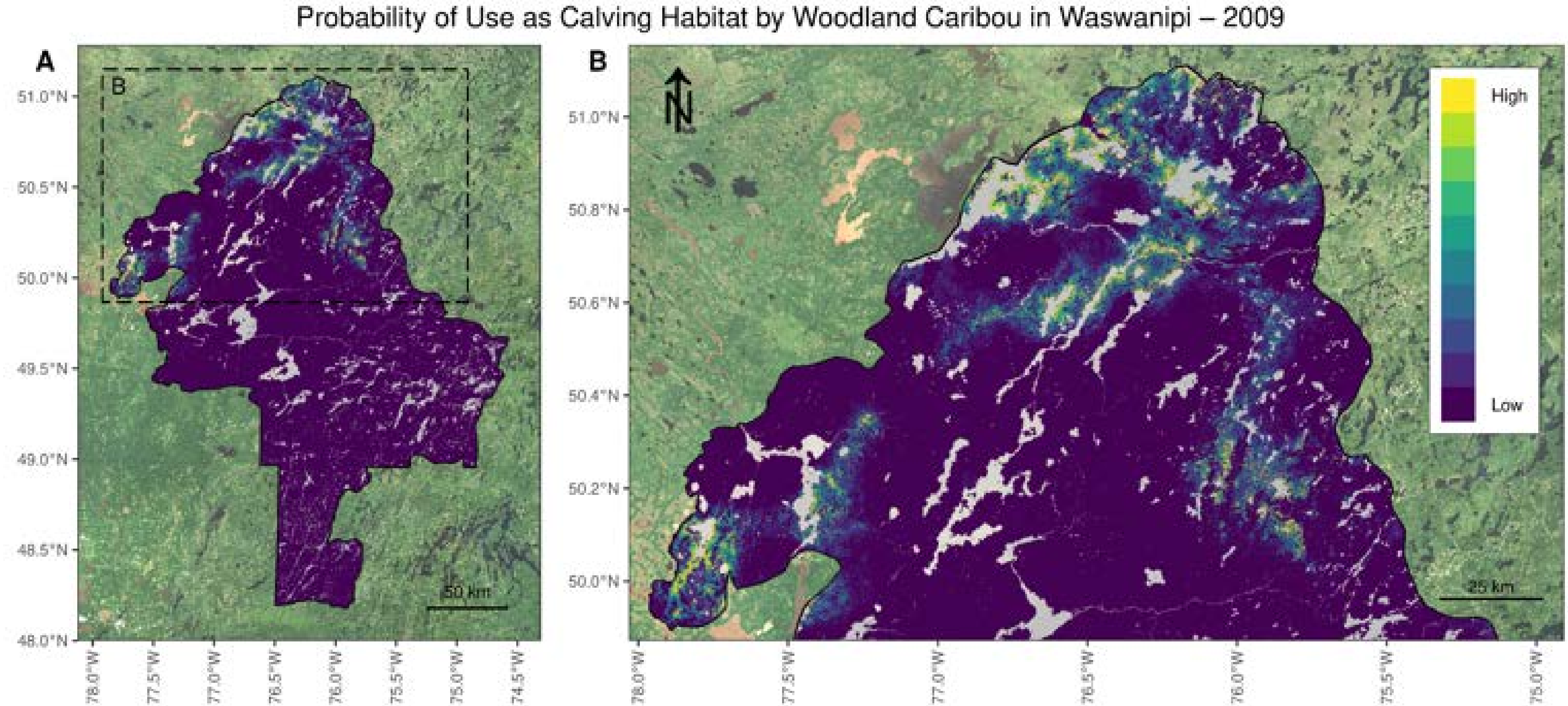
Supplementary Figure 3. Maps of probability of use as calving habitat in 2006 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



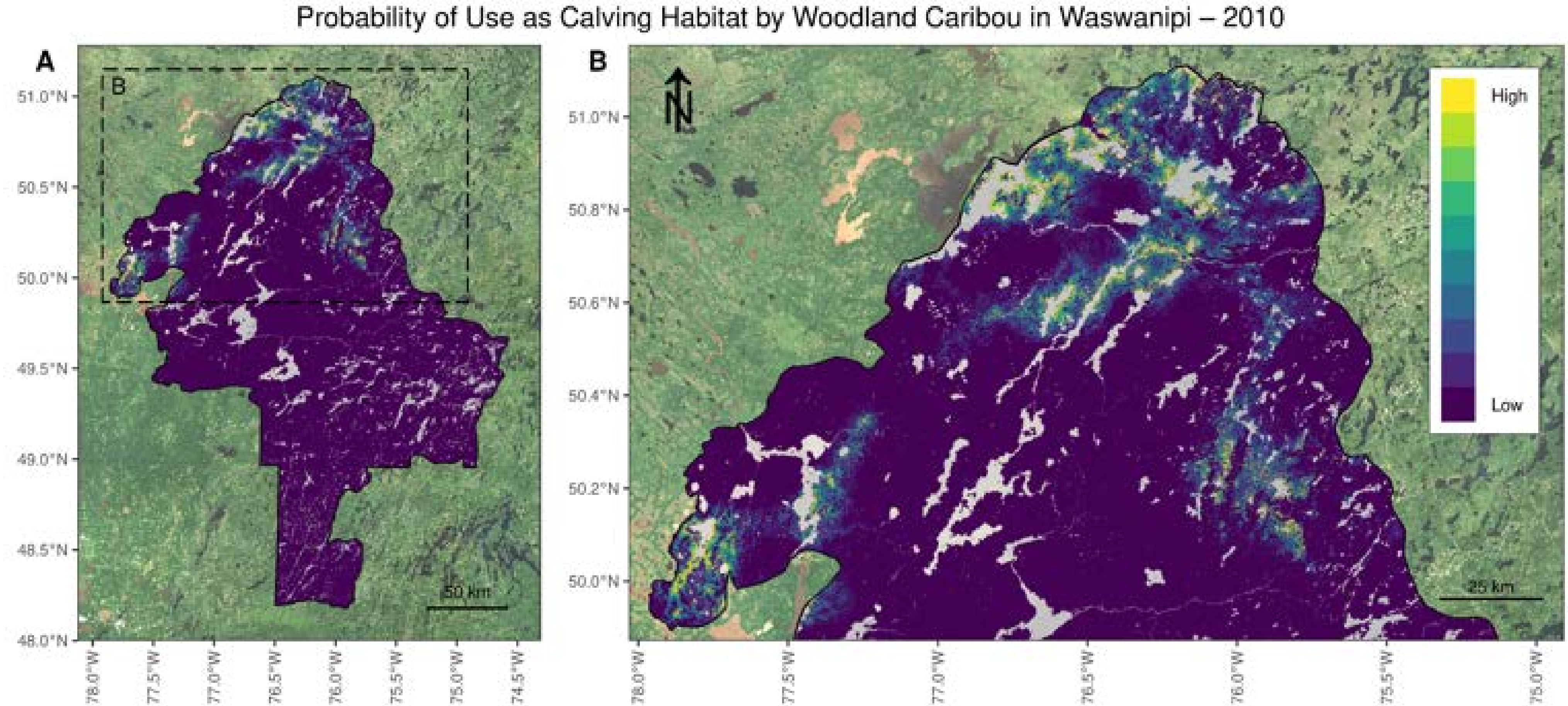
Supplementary Figure 4. Maps of probability of use as calving habitat in 2007 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



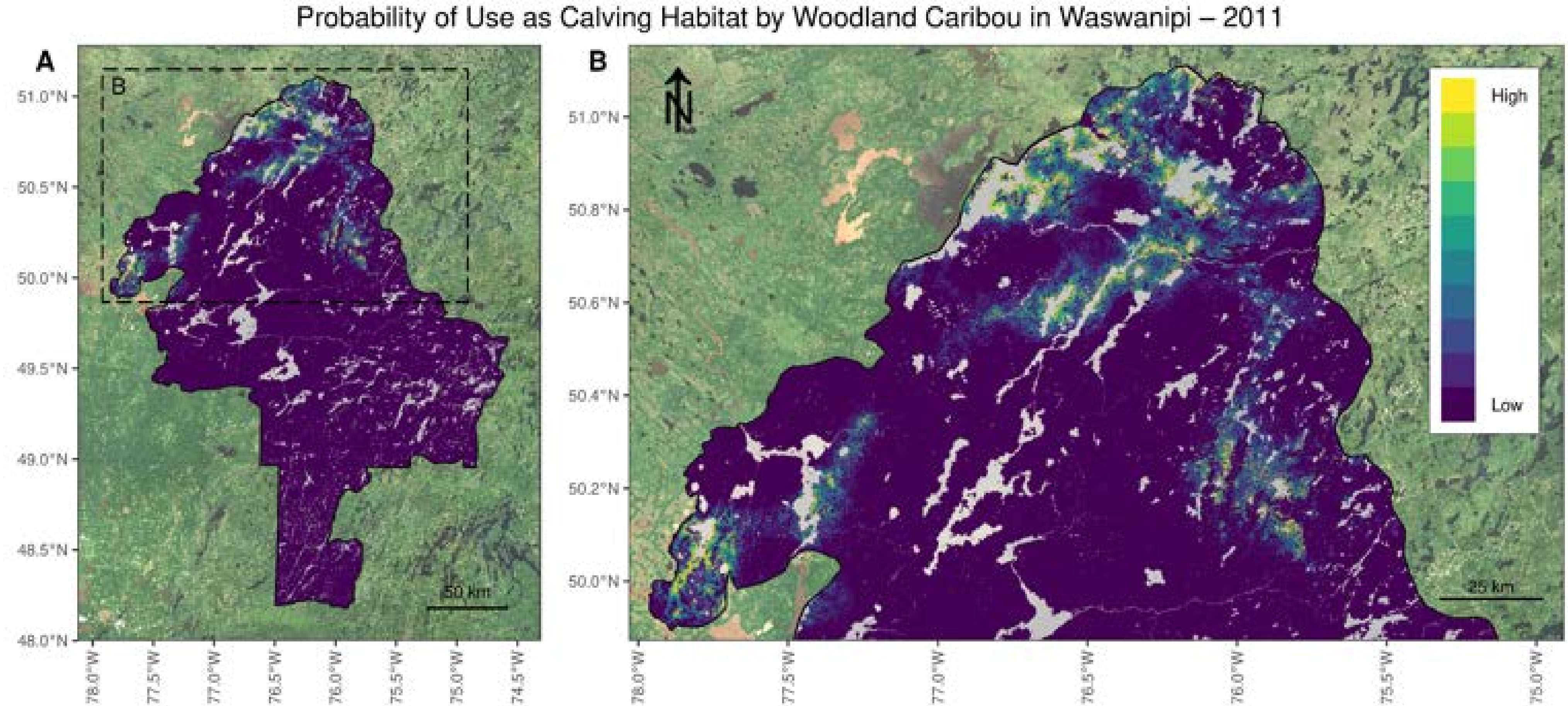
Supplementary Figure 5. Maps of probability of use as calving habitat in 2008 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



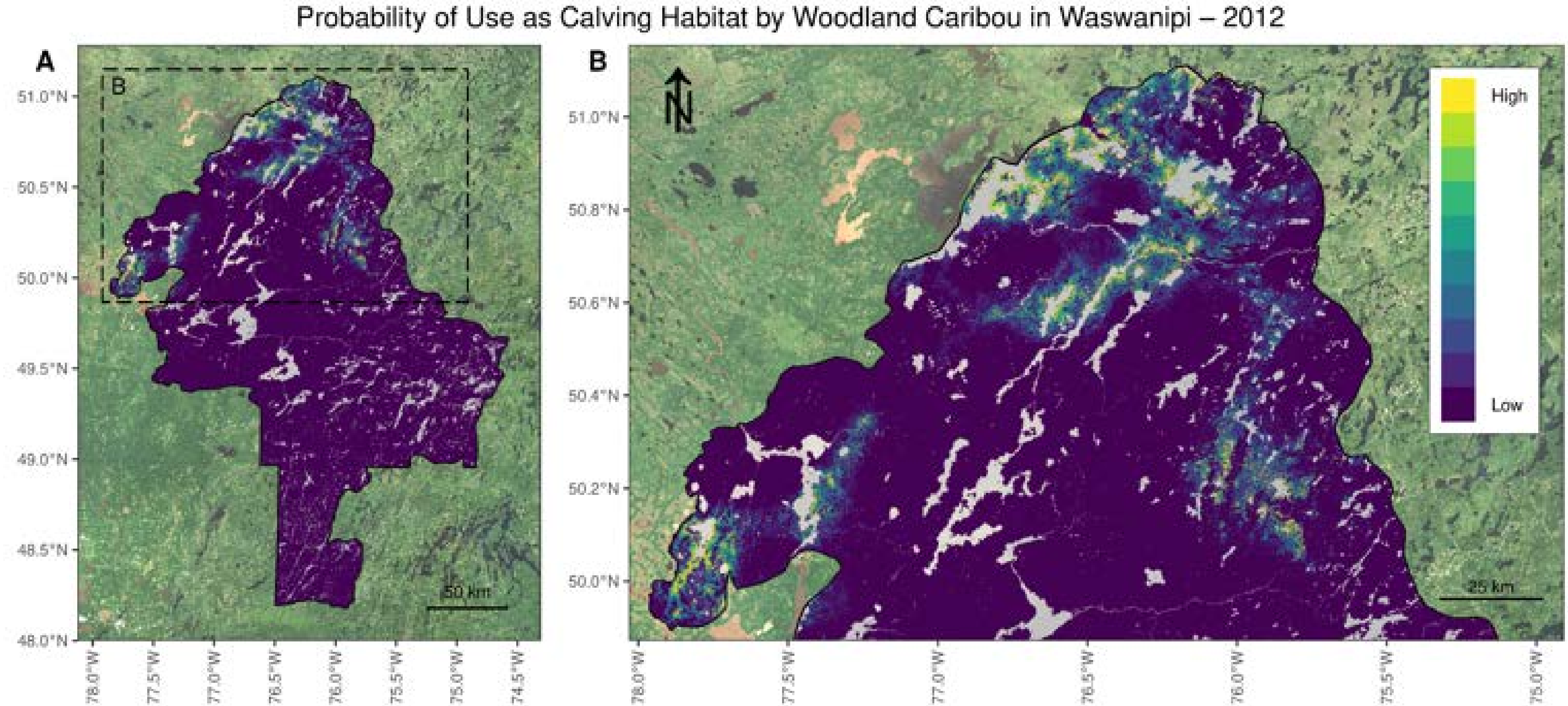
Supplementary Figure 6. Maps of probability of use as calving habitat in 2009 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



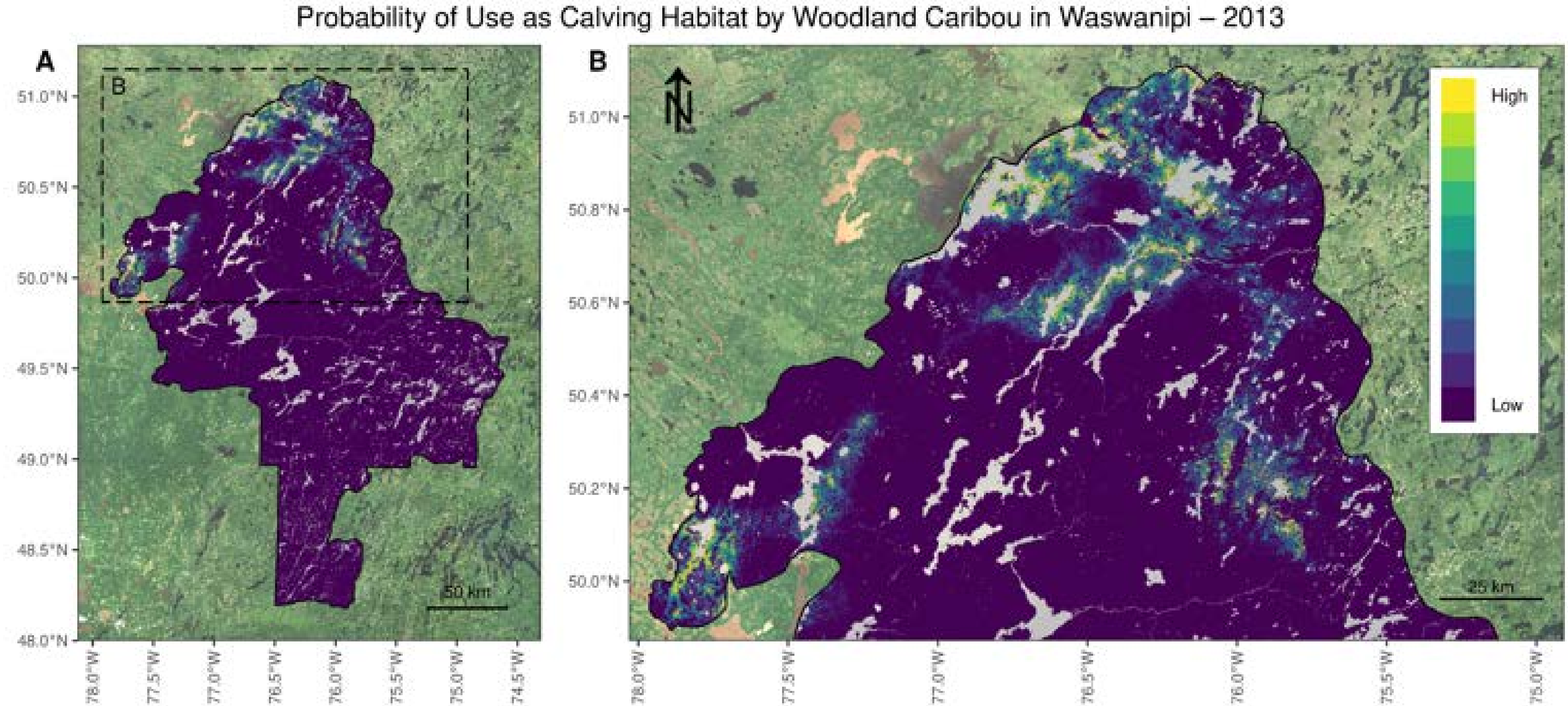
Supplementary Figure 7. Maps of probability of use as calving habitat in 2010 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



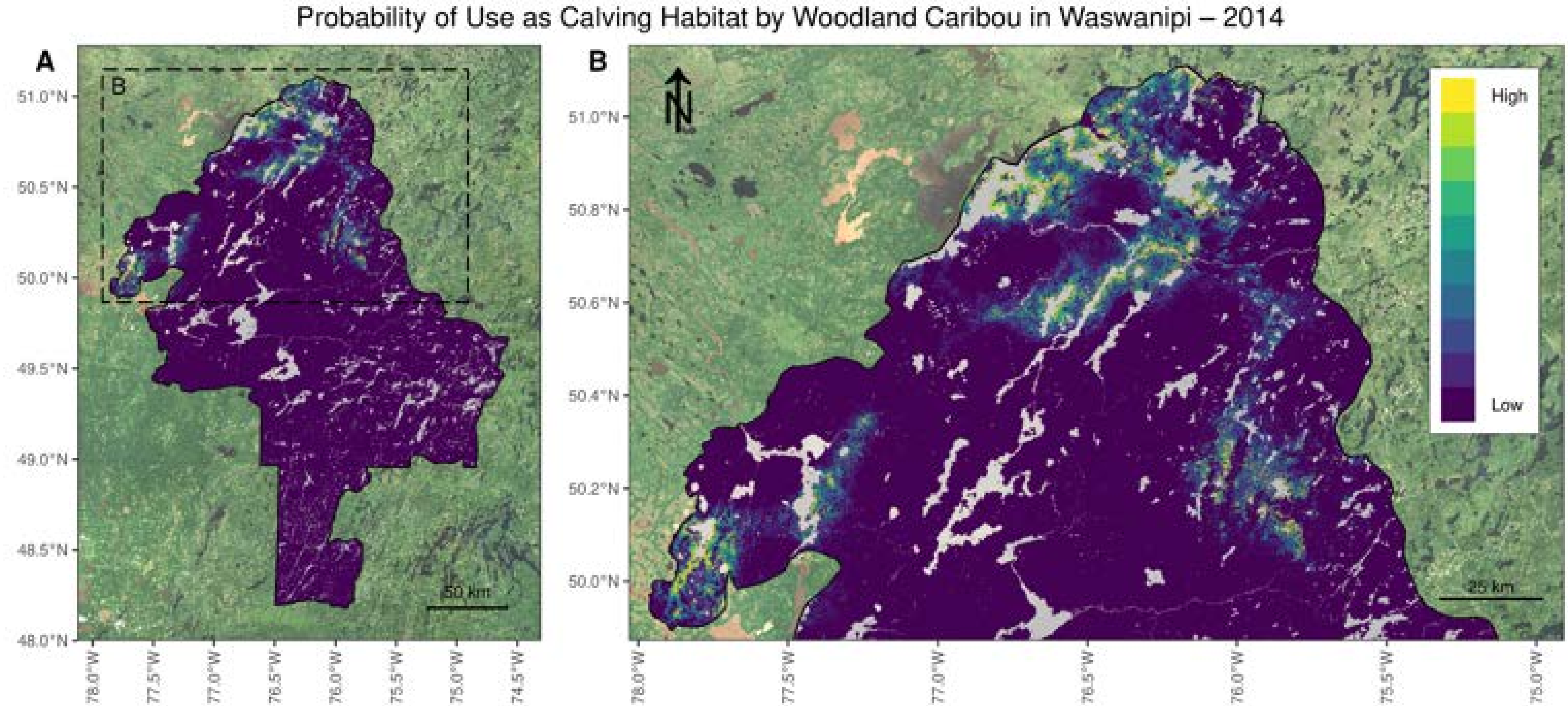
Supplementary Figure 8. Maps of probability of use as calving habitat in 2011 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



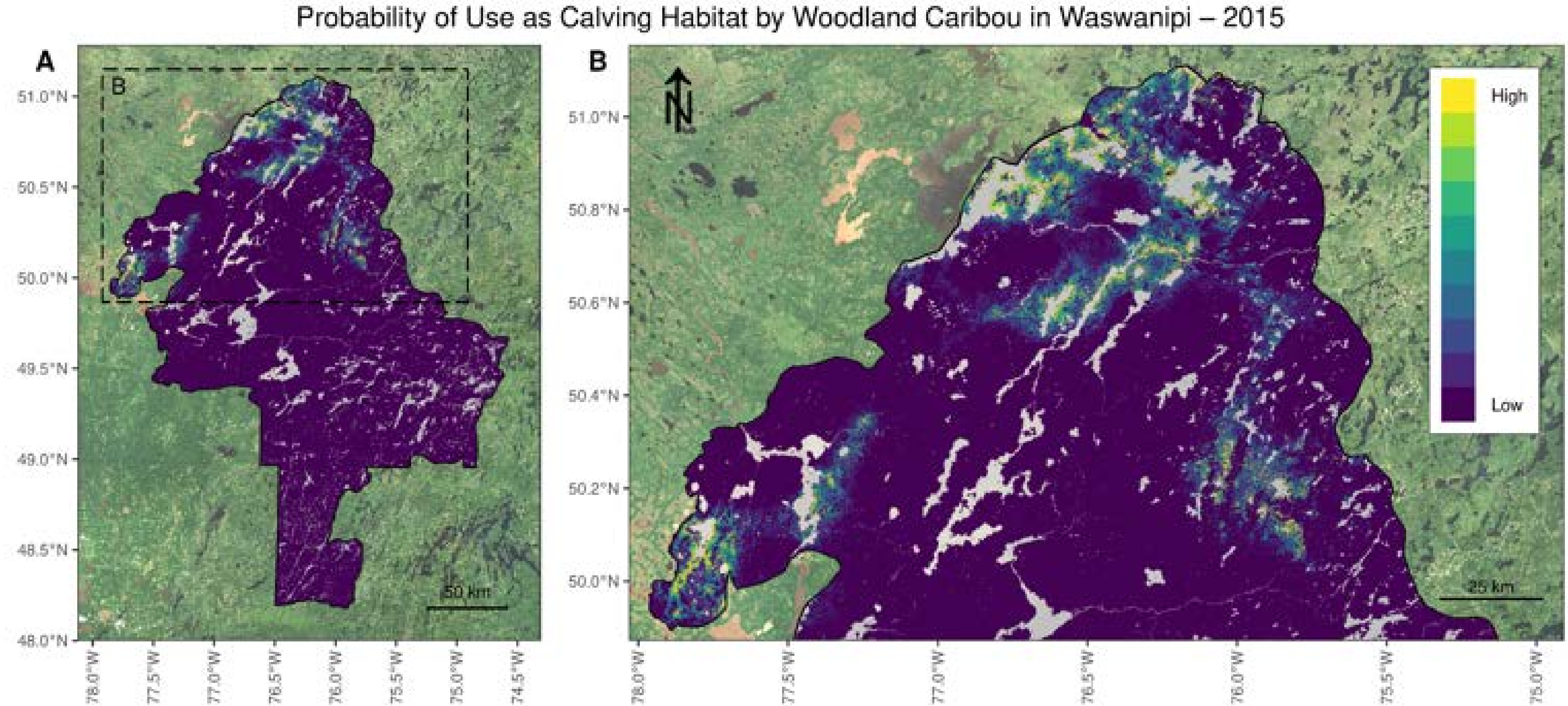
Supplementary Figure 9. Maps of probability of use as calving habitat in 2012 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



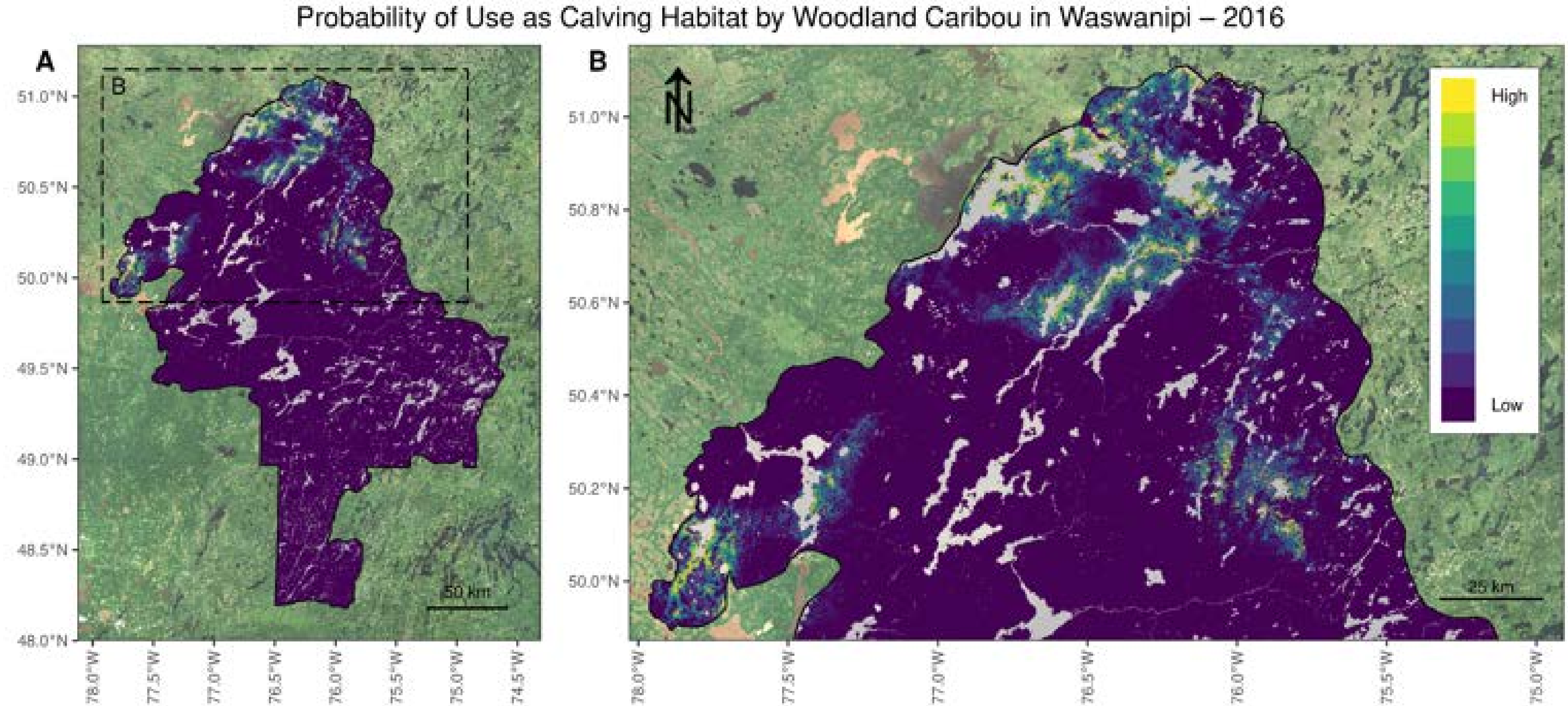
Supplementary Figure 10. Maps of probability of use as calving habitat in 2013 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



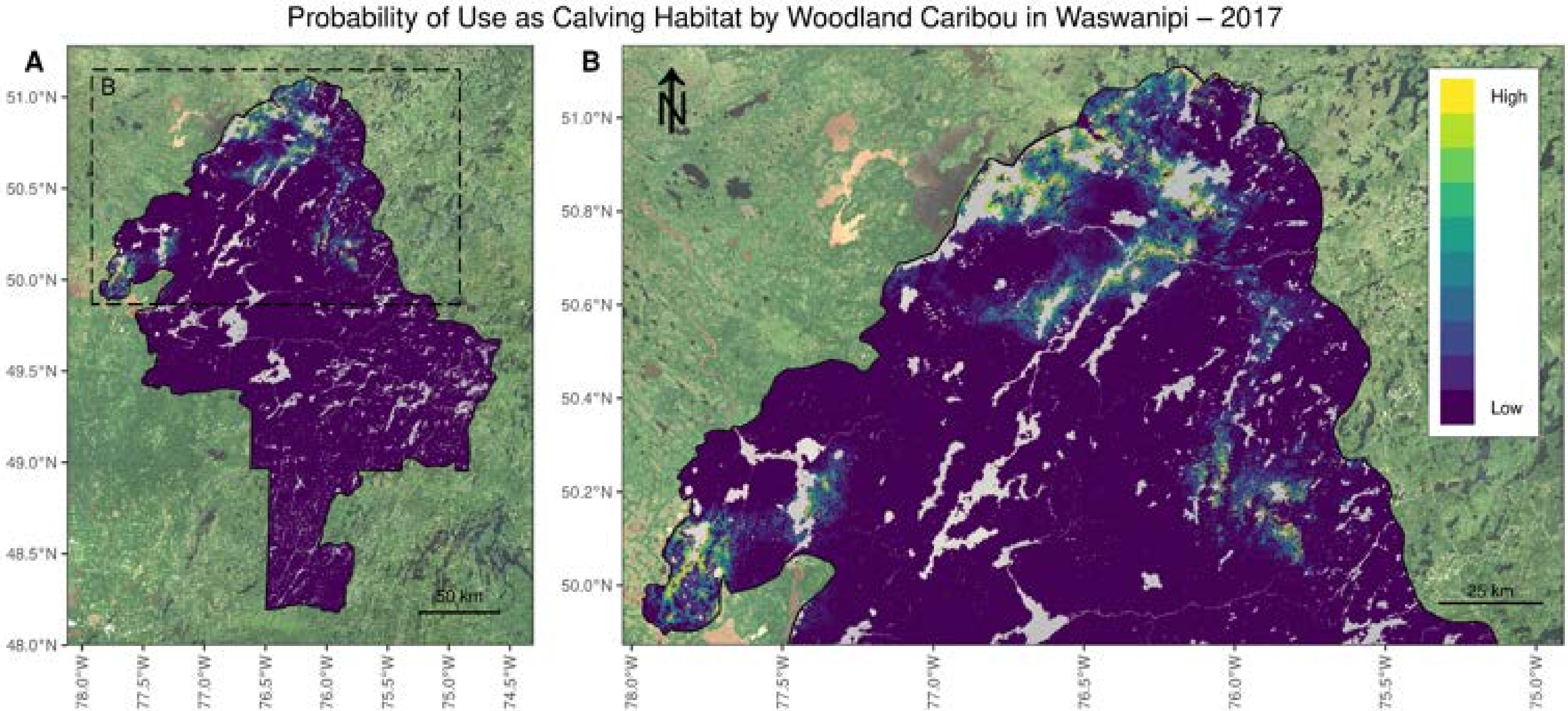
Supplementary Figure 11. Maps of probability of use as calving habitat in 2014 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



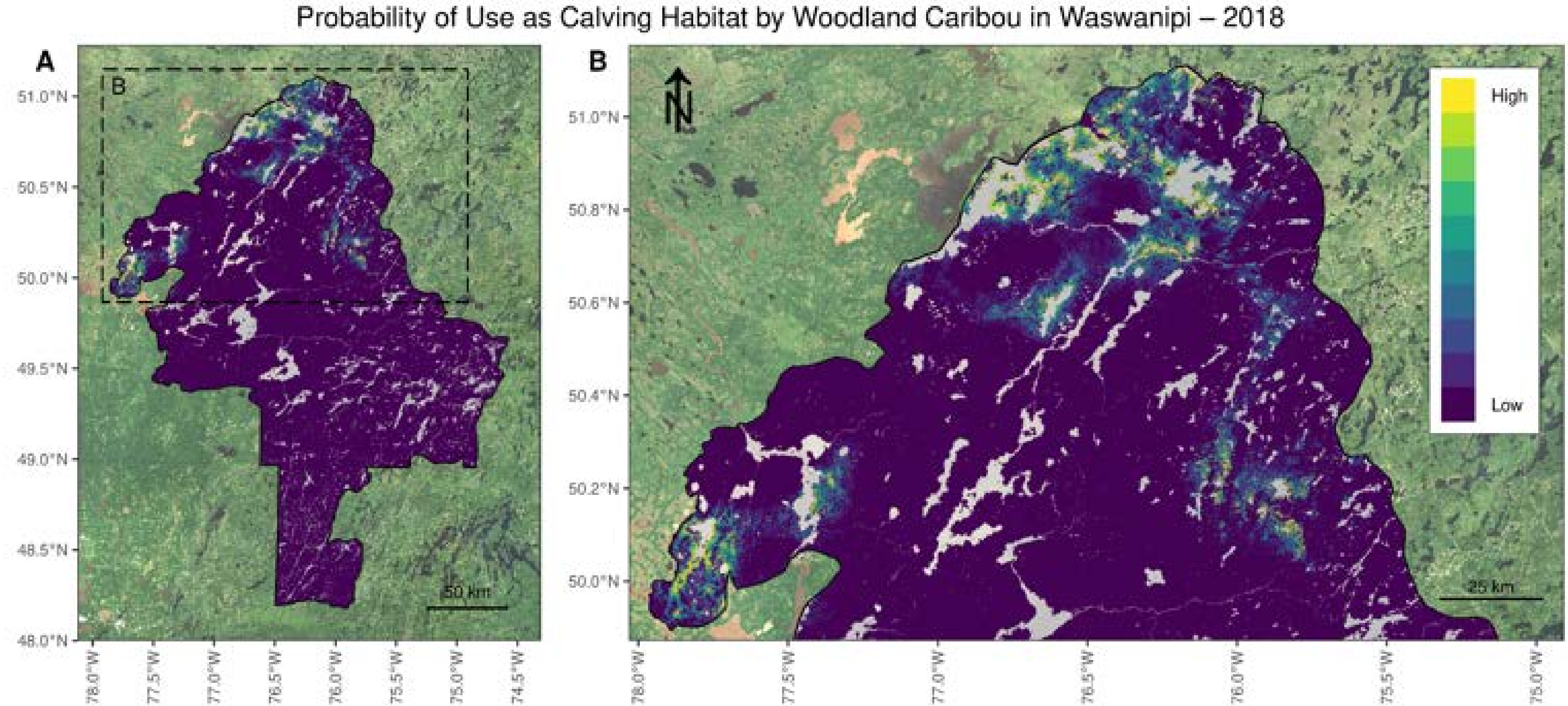
Supplementary Figure 12. Maps of probability of use as calving habitat in 2015 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



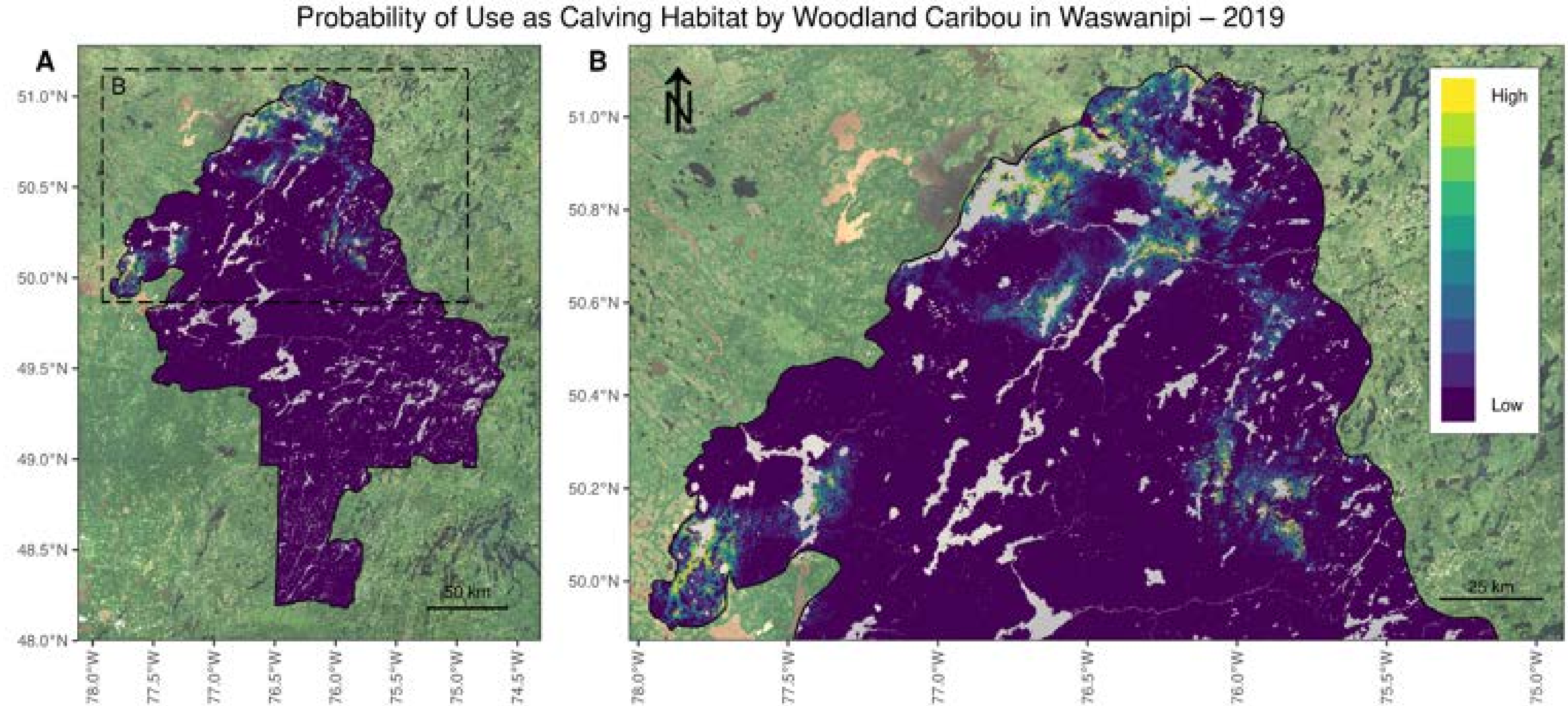
Supplementary Figure 13. Maps of probability of use as calving habitat in 2016 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



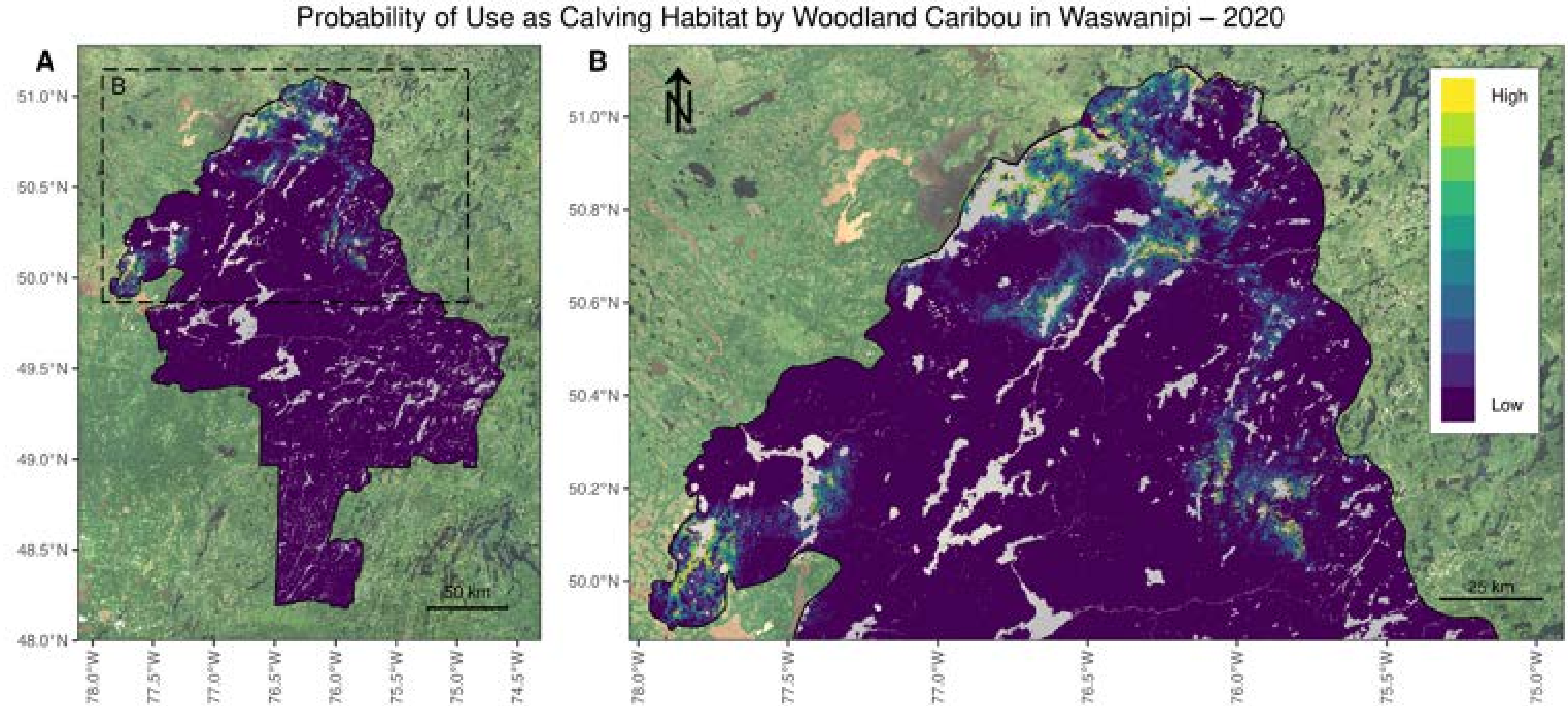
Supplementary Figure 14. Maps of probability of use as calving habitat in 2017 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



Supplementary Figure 15. Maps of probability of use as calving habitat in 2018 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



Supplementary Figure 16. Maps of probability of use as calving habitat in 2019 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.



Supplementary Figure 17. Maps of probability of use as calving habitat in 2020 (A) over the entire Waswanipi region and (B) in the northern part of the Waswanipi region. Probability of use as calving habitat was predicted using a resource selection function, and grouped into 10 equal-interval bins. Water bodies within Waswanipi are illustrated in grey. Basemap is a Sentinel-2 RGB annual median composite.