SUPPLEMENTARY MATERIALS

APPENDIX S1: Methods for generating data layers for conservation principles

All data layers were converted to raster and resampled at a 5-arc minute resolution (~10 km by 10 km grid). Data were normalized on a scale of 0 to 100 for each data layer, where 0 was equivalent to least need and 100 was equivalent to greatest need for protected areas. This scale enabled us to compare priorities across all conservation principles. A spatial analysis tool, with all data layers, is available at climaterefugia.ca/research/canada-target-1/conservation-planning-tool and can support tailored data exploration.

Data for Principle 1: Protecting species-at-risk

We obtained range map information for 490 species-at-risk in Canada listed under SARA, where range information was available on March 28, 2013. Range maps were derived from a combination of datasets including: Environment Canada geospatial dataset combined with COSEWIC assessments or recovery strategies, digitized maps from reports, and NatureServe (ECCC 2016). The density of species-at-risk was converted to a scale ranging from 0 for the minimum density of species-at-risk in the dataset (1 species) to 100 for the maximum (62 species). We assess the relative importance of different areas according to Principle 1 regardless of the extent of the species' range within Canada.

How much Canada should prioritize species whose ranges exist primarily outside of the country (i.e., peripheral transboundary species) has been debated. From a global perspective, and to maximize the effectiveness of conservation resources, Canada has substantial "global responsibility" to address declines for non-peripheral species with a significant amount of the total population or range within Canada (Bunnell et al. 2006). On the other hand, peripheral populations in Canada may be critically important in facilitating species' range shifts poleward in the face of climate change (Gibson et al. 2009; Rehm et al. 2015). Interestingly, peripheral populations can be less prone to extinction than core populations (Channell and Lomolino 2000; Laliberte and Ripple 2004). We recommend evaluating Principle 1 by first assuming that all species-at-risk in Canada are equally valuable and then weighting each species according to the global responsibility that Canada has for that species (e.g., using the categorical system of Bunnell et al. 2006).

Data for Principle 2: Representing ecosystem diversity

Data on current protected areas in Canada were obtained through the Canadian Council on Ecological Areas - Conservation Areas Reporting and Tracking System (CARTS). We excluded protected areas that were non-terrestrial or do not currently meet CBD standards for protection (i.e., CARTS status listed as uncertain or not applying towards Aichi 11 targets). The average amount of terrestrial-based protected areas was calculated for each ecoregion (ESWG 1995). Ecoregions were then normalized on a scale of 0 (greater than or equal to 10% protected areas within ecoregion; meets Aichi Target 11) indicating that the minimum representativeness target is currently met to 100 (no protected areas within ecoregion). Although 10% protected areas within ecoregions is unlikely to be sufficient based on ecological criteria (Svancara et al. 2005; Noss et al. 2012; Dinerstein et al. 2017; Locke 2015), this threshold was used to illustrate major policy based gaps in protecting ecoregions of Canada.

Data for Principle 3: Conserving remaining wilderness

Within Canada, land-use legacies affect levels of disturbance, ranging from regions with high human density and/or high levels of resource extraction to wilderness areas that remain in a relatively intact state. Based on a combination of data sources (European Space Agency land cover 2017 maps.elie.ucl.ac.be/CCI/viewer/; gridded population of the world version 4 2015 sedac.ciesin.columbia.edu/; Global Forest Watch Canada intact forest and Canada access data.globalforestwatch.org/), we identify regions that are heavily settled and/or cultivated for agriculture. Regions of resource extraction are identified using data from the Global Forest Watch Canada - Canada Access dataset (data.globalforestwatch.org/) based on combined anthropogenic land surface disturbances caused mainly by industrial activities, including, but not limited to, roads, mines, forestry clear cuts, well sites, pipelines, transmission lines, and agricultural clearings. Wilderness regions represent the part of the Canadian landmass that is not densely settled, cultivated, or involved in intensive resource extraction; this definition of wilderness includes areas with traditional Indigenous land uses. In order to emphasize the importance of large intact wilderness regions uninterrupted portions of wilderness land that exceeded 5000 km^2 (see Gurd et al. 2001; Leroux et al. 2007) were ranked at a priority of 100 while wilderness lands < 5000 km^2 were ranked at a priority of 50.

Data for Principle 4: Ensuring connectivity and resilience

Within Canada, we developed a connectivity measure based on two data sources that prioritize key areas for connectivity: connectivity initiatives and riparian zones (each scaled between 0 and 50), and then summed for a total value out of 100. Connectivity datasets span spatial extents ranging from national/international connectivity initiatives to fine-scale riparian connectivity.

The use of multiple approaches to quantifying connectivity priorities (Hannah et al. 2007) can reduce bias inherent in any single approach (Watson et al. 2008) and promote resilience.

(a) We incorporated data on current large landscape conservation initiatives (Algonquin to Adirondack, Boreal Songbird Initiative, Two Countries One Forest, Yellowstone to Yukon) that include efforts to protect and connect habitat (Figure S4). Lands identified as important for connectivity by one or more of these initiatives were coded as present (50) and otherwise pixels were coded as 0 (binary coding). While we highlight existing large landscape conservation initiatives as a focus, a minimum standard of connectivity may also be relevant at a national scale (i.e., increasing functional connectivity across the country). Irrespective, with the exception of isolated protected areas, increasing protected areas across Canada is likely to make progress towards the second aim. As such we do not assess current baseline connectivity.

(b) Riparian corridors protect both terrestrial and freshwater habitats and contribute to local scale connectivity, while allowing access of wildlife to water. We generated buffers around lakes and on either side of major rivers (CANVEC 2013). The importance of protecting riparian habitat was treated in a graded way, with areas given a 0-50 value from high importance (assigned a value of 50 if within 0-175 m from the river center or lake edge), intermediate importance (assigned a value of 37.5 if within 175-350 m), low importance (assigned a value of 25 if within 350-1450 m), to non-riparian (assigned a value of 0 if beyond 1450 m). This scale gives extra weight to riparian buffer strips within 175 m of a waterway because they contribute to numerous ecosystem functions, including: soil retention, filtration, and local cooling effects (EC 2013; Aguiar et al. 2015; Johnson and Wilby 2015; Styles et al. 2016). Nevertheless, neighbouring areas (~ 350-1450 m) are also important and provide functional habitat and movement corridors for large mammals (Hilty and Merenlender, 2004). The two connectivity metrics (i.e., connectivity initiatives, and riparian zones) were summed, so that each contributed equally to the total connectivity principle.

Data for Principle 5: Preserving climate refugia

Climate change impacts biodiversity based on: (i) how fast climate changes at a single location through time (velocity); (ii) how much climate deviates from local climate change trends (extremes); (iii) how much climate changes in a focal area relative to surrounding areas (refugia), and (iv) how well climate at point A connects to climate at point B within a set period of time (climate connectivity). We focus on the first three aspects, based on historical data (for clarity we describe these as "climate refugia"), but we note that modeling future climate change would allow inclusion also of spatial climate connectivity (see McGuire et al. 2016). Protecting areas with slower changes in environmental conditions relative to neighbouring regions can reduce biodiversity declines associated with climate change by reducing the physiological mismatch of a species to its historic environmental conditions (Albright et al. 2011, Devictor et al. 2012, Coristine and Kerr 2015).

We evaluated velocity, extremes, and refugia based on six climate variables measured between 1983-2013 (BIOCLIM01: mean annual temperature, BIOCLIM 05: temperature of warmest period, BIOCLIM06: temperature of coldest period, BIOCLIM13: precipitation in the wettest period, BIOCLIM 14: precipitation in the driest period, BIOCLIM15: precipitation seasonality, (Coristine et al. 2016; for climate data see Hutchinson 2004; McKenney et al. 2011). All climate variables were assessed on a per pixel basis using a comparison of relative climate changes according to:

$$\text{Mean (Focal Neighbourhood}_j\text{)} < \text{Mean (Focal Annulus}_j\text{)} - \text{SD (Focal Annulus}_j\text{)} \qquad \textbf{Equation 1}$$

(where $_j$ represents a respective climate variable, assessed for rate or variance of climate change through time, and the mean and standard deviation are calculated on all pixels (5-arcminute) within the area of interest) to identify potential for climate change stability. Focal neighbourhoods ranged in size from 40 – 200 km diameter. The annulus is a neighbourhood surrounding, but not containing, the focal neighbourhood and becomes the region for comparison. Both neighbourhood and annulus are maintained at approximately equal area.

Climatic changes were first categorized according to: how broadly low velocity and/or low extremes of climate change were preserved over space (i.e., the spatial region covered by focal neighbourhoods ranging from 40-200 km diameter); the number of climate variables with low velocity and/or few extremes of climate change; and the congruence between annual and seasonal preservation of low velocity and/or low extremes of climate change. For each pixel, climate changes within each category were deemed to exhibit climate refugia potential if they satisfied Equation 1. Per pixel, categories were then combined using a fuzzy sum overlay function (ESRI 2017).

Some sites may score well according to this fuzzy sum but still exhibit high flux for one or more of the climate change variables. We thus also excluded sites that were one standard deviation above the surrounding region for any of the six climate variables or categories. That is, pixels were excluded if:

Mean (Focal Neighbourhood$_j$) > Mean (Focal Annulus$_j$) + SD (Focal Annulus$_j$) **Equation 2**

The remaining sites were then ranked according to a fuzzy sum function. We identified 18.5% of the total land base as having potential climatic stability (i.e., 23,435 pixels). The values for all pixels were then rescaled so that the range fell between 100 (capturing the greatest number of climate variables exhibiting low velocity, low extremes, and refugia) and 0 (sites with no indication of low velocity, low extremes, or refugia).

APPENDIX S2: Key Biodiversity Areas

The IUCN established Key Biodiversity Area (KBA) approach is based on five criteria that apply at the species and ecosystem levels (IUCN 2016). These criteria are:

A. Threatened biodiversity
B. Geographically restricted biodiversity
C. Ecological integrity (wholly intact ecological communities with supporting large scale ecological processes
D. Biological processes (including demographic aggregations, ecological refugia, and recruitment sources)
E. Irreplaceability through quantitative analysis (very high irreplaceability as identified through a complementarity based analysis)

Sites identified under these criteria are significant for the persistence of a specific species or ecosystem (e.g., holding at least 20% of the global population of a species or being one of a limited number of areas (≤ 2) representing an ecoregion).

To date KBAs have been identified in Canada only for birds and freshwater areas. In addition, efforts are underway to identify sites meeting Criterion C, Ecological Integrity. However, improved availability of data from conservation data centers across Canada would allow the identification under criteria A (Threatened Biodiversity) and B (Range Restricted Biodiversity).

Supplementary Box S1. Potential threats to biodiversity (IUCN Threats Classification Scheme, Version 3.2).

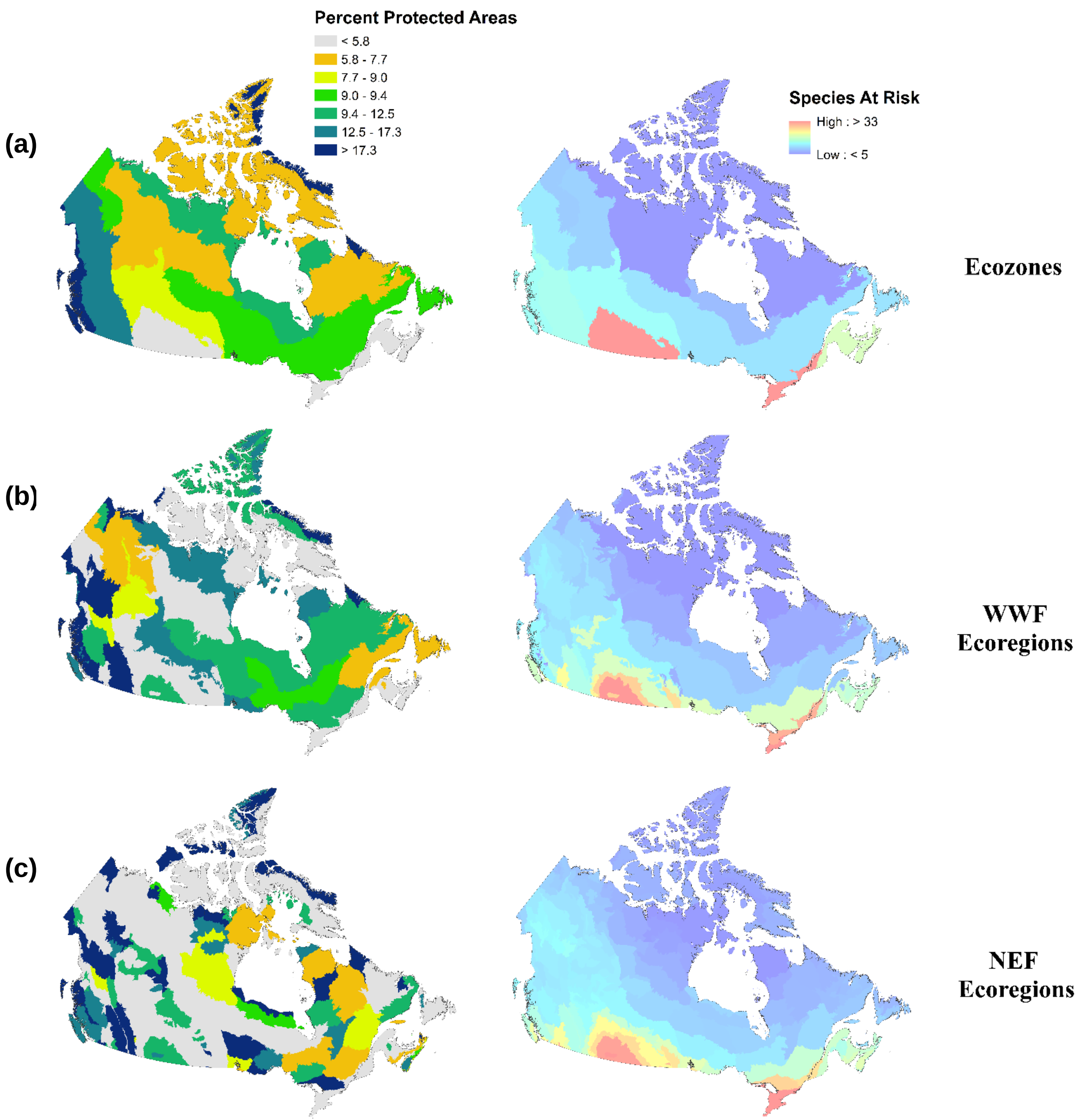
1. Residential and Commercial Development
Housing & urban areas, commercial & industrial areas, tourism & recreation areas
2. Agriculture and Aquaculture
Annual & perennial non-timber crops, wood & pulp plantations, livestock farming & ranching, marine & freshwater aquaculture
3. Energy Production and Mining
Oil & gas drilling, mining & quarrying, renewable energy
4. Transportation and Service Corridors
Roads & railroads, utility & service lines, shipping lanes, flight paths
5. Biological Resource Use
Hunting & collecting terrestrial animals, gathering terrestrial plants, logging & wood harvesting, fishing & harvesting aquatic resources
6. Human Intrusions and Disturbance
Recreational activities, war, civil unrest & military exercises, work & other activities
7. Natural Systems Modification
Fire & fire suppression, dams & water management/use, other ecosystem modifications
8. Invasive and other Problem Species, Genes & Diseases
Invasive non-native/alien species/diseases, problematic native species/diseases,introduced genetic material, problematic species/diseases of unknown origin, viral/prion-induced diseases, diseases of unknown cause
9. Pollution
Domestic & urban waste water, industrial & military effluents, agricultural & forestry effluents, garbage & solid waste, air-borne pollutants, excess energy
10. Geological Events
Volcanoes, earthquakes/tsunamis, avalanches/landslides
11. Climate Change and Severe Weather
Habitat shifting & alteration, droughts, temperature extremes, storms & flooding, other impacts
12. Other Options
Other threats

Supplementary Table S1: The top 30 ecoregions containing sites with the highest composite score across the five principles. Differences in scores between the two weighting methods highlight the impact of land-use legacy on protected area import. Where multiple land-use histories co-occur within an ecoregion (under the relative weighting) only the highest priority index value for a single land-use in the ecoregion is provided. Mean values are indicative of the overall priority for an ecoregion while maximum values are indicative of site specific priority (at the pixel level).

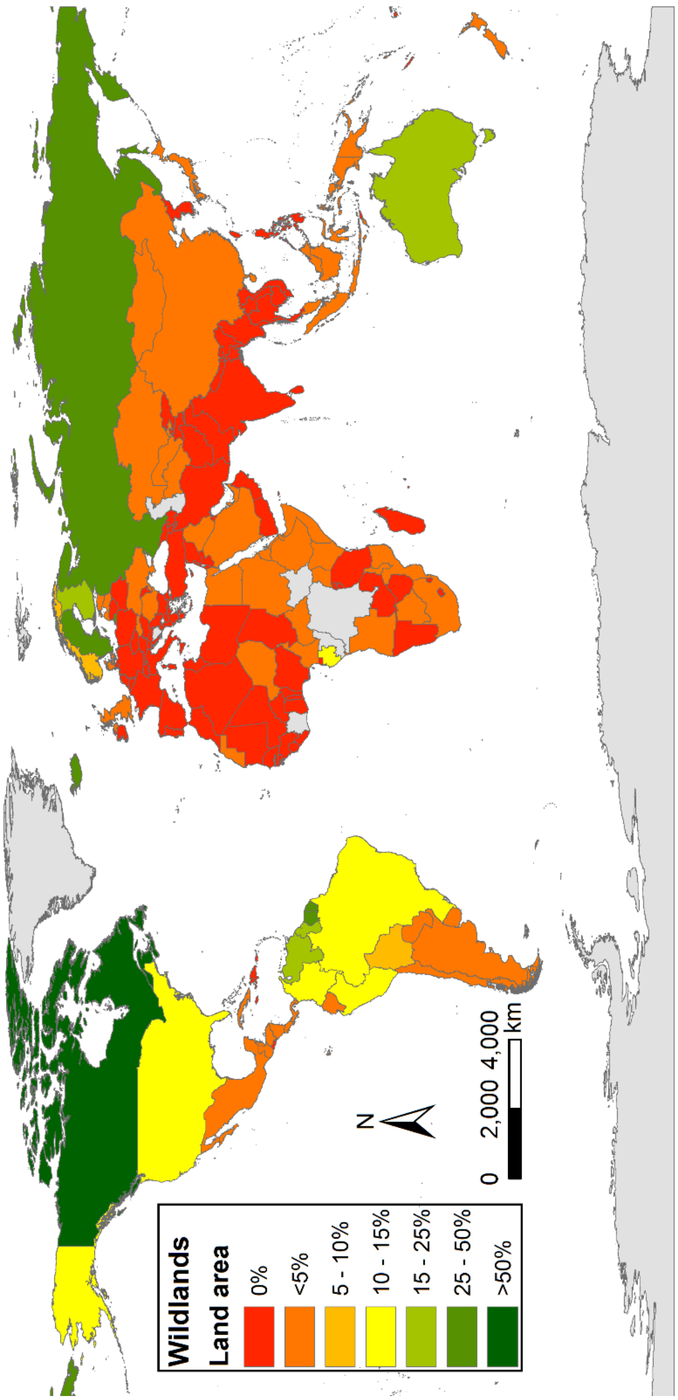
	EQUAL WEIGHTING		RELATIVE TO LAND-USE LEGACY		
ECOREGION	**Maximum**	**Mean**	**Maximum**	**Mean**	**Land-Use**
Appalachians	-	-	99.99	60.70	urban/resource
Athabasca Plain	88.71	59.68	87.01	55.63	wild
Churchill River Upland	93.66	54.26	92.71	49.92	wild
Coastal Barrens	88.76	64.43	87.08	59.44	urban/wild
Coppermine River Upland	94.21	67.65	93.34	62.95	resource/wild
Dease Arm Plain	87.14	55.73	-	-	
Fort MacPherson Plain	84.60	65.08	-	-	
Franklin Mountains	86.50	66.38	-	-	
Grandin Plains	95.08	77.63	94.34	74.27	wild
Great Slave Lake Plain	100.00	71.93	100.00	69.32	wild
Hayes River Upland	89.14	58.52	87.51	55.74	wild
Interlake Plain	94.14	53.00	96.47	60.37	urban/resource/wild
James Bay Lowlands	95.43	62.95	94.74	58.86	wild
Kingarutuk-Fraser River	96.80	63.13	96.32	58.16	wild
Klondike Plateau	97.12	67.86	96.68	67.30	resource/wild
Lake Manitoba Plain	-	-	92.10	51.06	urban
Liard Basin	92.73	63.78	91.64	61.34	resource/wild
Long Range Mountains	83.54	50.40	-	-	
Mackenzie Mountains	90.56	70.05	89.15	65.74	wild
Mackenzie River Plain	91.79	62.43	90.55	67.48	urban/resource/wild
Maguse River Upland	88.43	59.06	86.70	52.99	wild
Manitoulin-Lake Simcoe	-	-	94.30	55.08	urban/resource
Mecatina River	93.97	70.10	93.07	66.39	wild
Mid-Boreal Lowland	91.89	56.40	90.67	57.31	urban/resource/wild
Mid-Boreal Uplands	83.55	33.36	92.40	34.07	resource/wild

New Quebec Central Plateau	86.69	51.78	-	-	
Northern Alberta Uplands	-	-	91.83	54.71	resource
Peace Lowland	92.77	46.44	100.00	60.34	urban/resource/wild
Peel River Plateau	88.46	63.26	86.72	60.19	resource/wild
Pelly Mountains	97.05	73.98	96.61	71.69	resource/wild
Smallwood Reservoir-Michikamau	97.29	64.61	96.88	63.66	resource/wild
Takijua Lake Upland	87.47	59.17	-	-	
Wabasca Lowland	89.64	46.99	88.09	60.50	urban/resource/wild
Western Alberta Upland	-	-	91.89	59.88	urban/resource
Western Boreal	-	-	92.41	62.16	urban/resource
Yukon Plateau-North	95.23	61.68	94.51	58.48	resource/wild

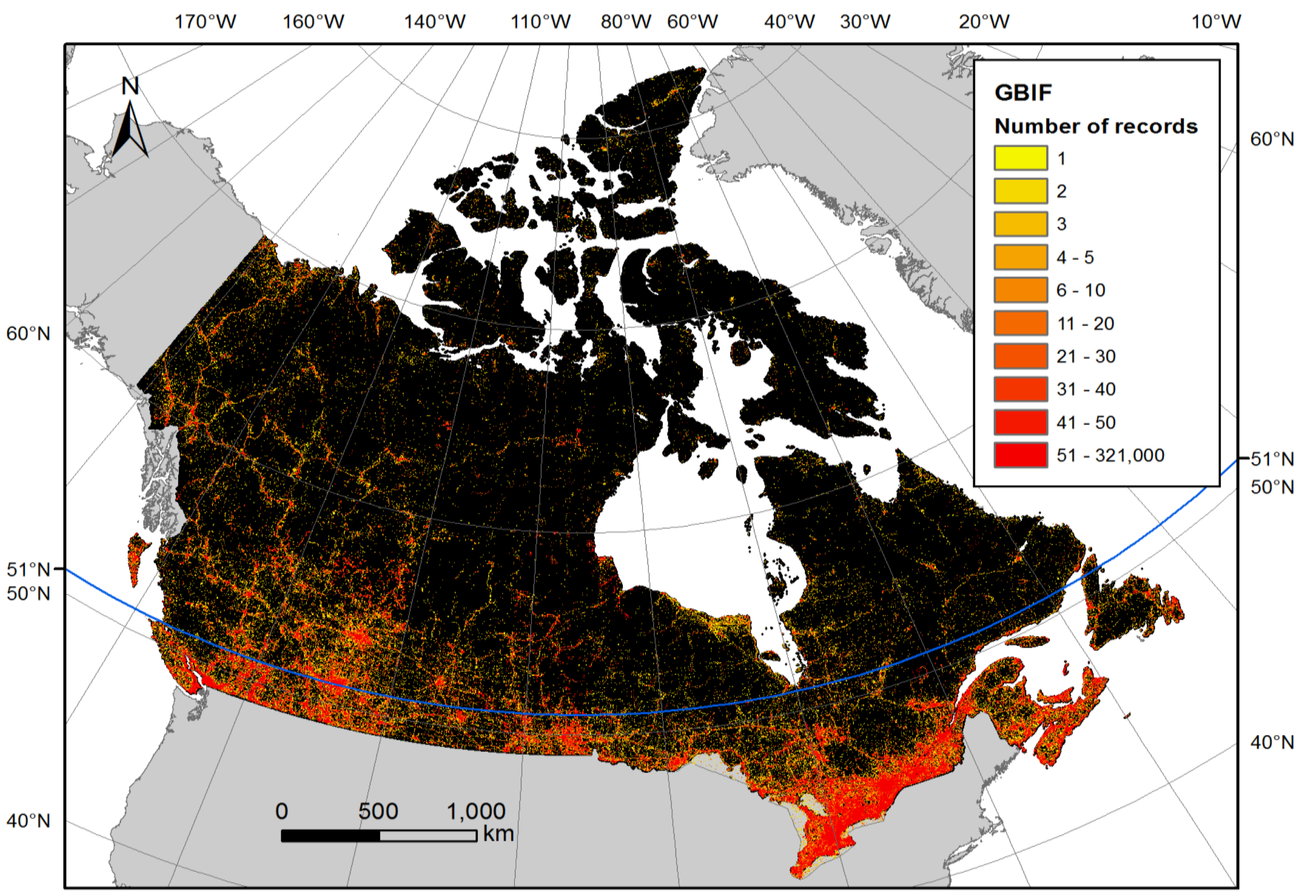
Supplementary Figure S1: Differences in protected area attainment and species-at-risk assessment based on method of categorization for representativity. Panels depict (a) ecozones, (b) World Wildlife Fund global ecoregions, and (c) Canada-specific National Ecological Framework ecoregions.



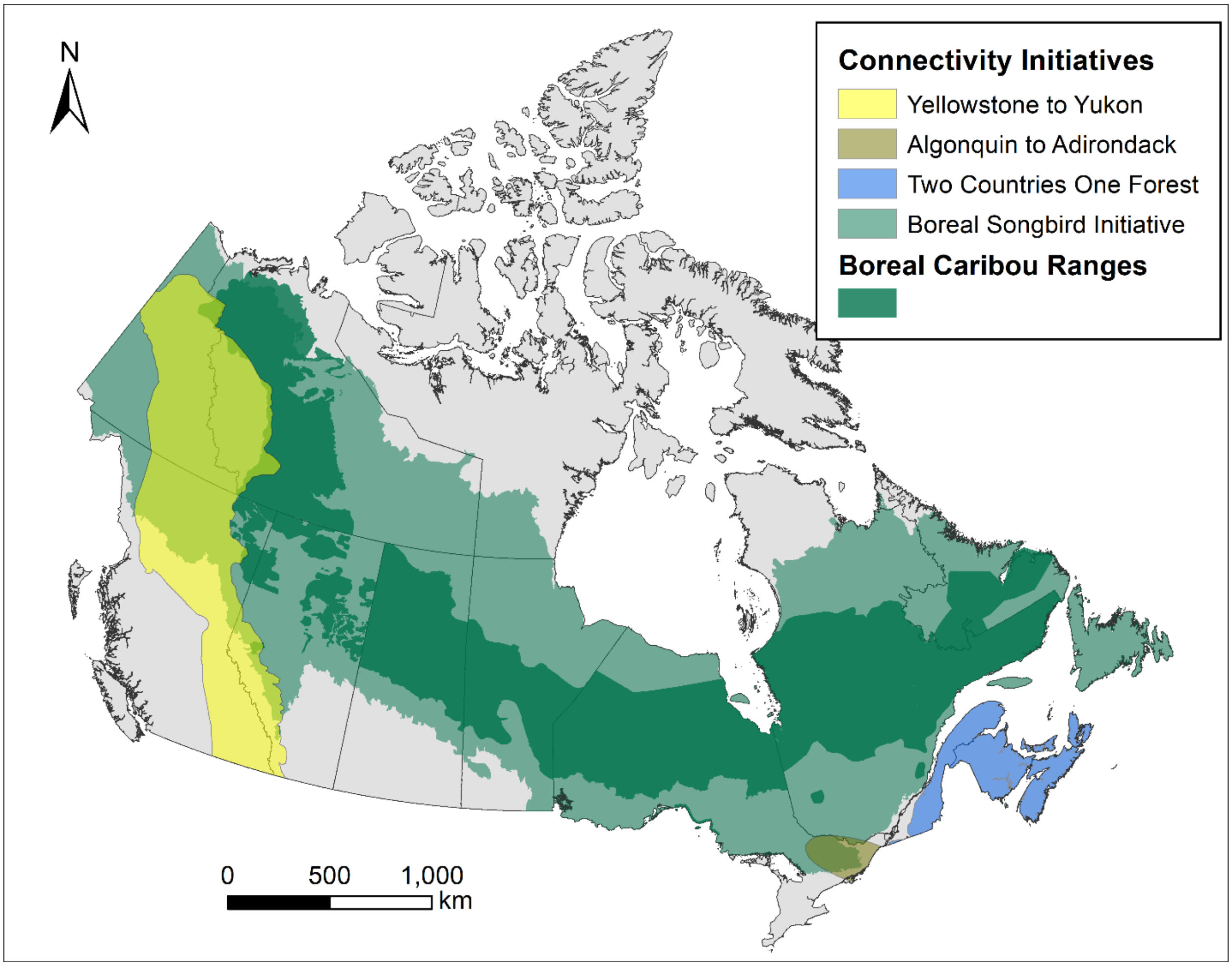
Supplementary Figure S2: Ice-free and non-barren wildlands as a percent of terrestrial land area for countries around the world (data based on Ellis and Ramankutty 2008). Dark gray regions represent countries with insufficient data.



Supplementary Figure S3: Data points for species observed in Canada (gbif.org; accessed: June 12, 2017) and summarized in a 4 km^2 grid. The clustering of points shows the strong bias in recorded data from southern Canada, relative to equal sampling across the country, indicating that information about biodiversity is increasingly sparse in the north. Of the 28.5 million occurrence records, only 15.1% are above 51° latitude (the blue line on the map).



Supplementary Figure S4: Four major landscape connectivity initiatives within Canada working towards increased habitat protection and connection of public and private lands. The threatened boreal caribou has the entirety of its range contained within the Boreal Songbird Initiative.



REFERENCES

Aguiar T Jr., Rasera K, Parron L, Brito A, and Ferreira M. 2015. Nutrient removal effectiveness by riparian buffer zones in rural temperate watersheds: the impact of no-till crops practices. Agricultural Water Management 149:74-80.

Albright TP, Pidgeon AM, Rittenhouse CD, Clayton MK, Flather CH, Culbert PD, et al. 2011. Heat waves measured with MODIS land surface temperature data predict changes in avian community structure. Remote Sensing of Environment 115:245-254.

Bunnell F, Kremsater L, and Houde I. 2006. Applying the Concept of Stewardship Responsibility in British Columbia. Biodiversity BC, Victoria, BC. 188 pp.

CANVEC. 2013. CANVEC 15 Meter hydro features of Canada. A Joint Initiative from the National Topographic Data Base, the Mapping the North process conducted by the Canada Center for Mapping and Earth Observation, the Atlas of Canada, and the GeoBase initiative. http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/shp/Hydro/.

Center for International Earth Science Information Network - CIESIN - Columbia University. 2016. Gridded Population of the World, Version 4 (GPWv4): population density. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY. DOI: 10.7927/H4NP22DQ.

Channell R, and Lomolino MV. 2000. Trajectories to extinction: spatial dynamics of the contraction of geographical ranges. Journal of Biogeography 27:169-179. DOI: 10.1046/j.1365-2699.2000.00382.x

Coristine L, and Kerr JT. 2015. Temperature-related geographical shifts among passerines: contrasting processes along poleward and equatorward range margins. Ecology & Evolution 5: 5162-5176.

Coristine LE, Soares RN, Soroye P, Robillard C, and Kerr JT. 2016. Dispersal limitation, climate change, and practical tools for butterfly conservation in intensively used landscapes. Natural Areas Journal 36:440-452.

Devictor V, van Swaay C, Brereton T, Brotons L, Chamberlain D, Heliola J, et al. 2012. Differences in the climatic debts of birds and butterflies at a continental scale. Nature Climate Change 2:121-124. DOI: 10.1038/nclimate1347.

Dinerstein E, Olson D, Joshi A, Vynne C, Burgess ND, Wikramanayake E, et al. 2017. An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67: 534-545.

Ellis EC, and Ramankutty N. 2008. Putting people in the map: anthropogenic biomes of the world. Frontiers in Ecology and the Environment 6: 439-447.

Environment and Climate Change Canada (ECCC). 2016. Species at Risk range dataset for species that are either an ECCC responsibility or a joint Parks Canada—ECCC responsibility, and that were SARA Schedule 1 listed as of March 28th 2013. SARA Management and Regulatory Affairs.

Environment and Climate Change Canada (ECCC). 2017. Boreal caribou ranges in Canada [online]: Available from donnees.ec.gc.ca/data/species/protectrestore/boreal-caribou-ranges-in-canada/.

Environment Canada. 2013. How much habitat is enough? 3rd edition. Environment Canada, Toronto, Ontario.

ESRI. 2017. ArcGIS Desktop: Release 10.4.1 Redlands. Environmental Systems Research Institute, Redlands, California.

ESWG. 1995. Ecological Stratification Working Group; A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull. Accessed 2017-05-10

European Space Agency Climate Change Initiative. 2017. Land Cover project 2014-2017. Land Cover map 2015, [online]: Available from maps.elie.ucl.ac.be/CCI/viewer/download.php.

Gibson SY, Van der Marel RC, and Starzomski BM. 2009. Climate change and conservation of leading-edge peripheral populations. Conservation Biology 23:1369-1373.

Global Administrative Areas. 2015. GADM database of Global Administrative Areas, version 2.8, [online]: Available from gadm.org.

Global Biodiversity Information Facility. 2017. Species occurrence data [online]: Available from gbif.org.

Global Forest Watch Canada. 2014. Canada Access 2010, [online]: Available from data.globalforestwatch.org/.

Global Forest Watch Canada. 2016. Canada's Intact Forest Landscapes 2013 Dataset, [online]: Available from data.globalforestwatch.org/.

Gurd DB, Nudds TD, and Rivard DH. 2001. Conservation of mammals in eastern North American wildlife reserves: How small is too small? Conservation Biology 15: 1355-1363.

Hannah L, Midgley G, Andelman S, Araújo M, Hughes G, Martinez-Meyer E, et al. 2007. Protected area needs in a changing climate. Frontiers in Ecology and the Environment 5:131-138.

Hilty JA, and Merenlender AM. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. Conservation Biology 18:126-135.

Hutchinson MF. 2004. ANUSPLIN Version 4.3. Fenner School of Environment and Society, Australian National University, Australia. Available from http://fennerschool.anu.edu.au/research/products.

IUCN. 2016. A Global Standard for the Identification of Key Biodiversity Areas, Version 1.0. First edition. Gland, Switzerland: IUCN.

Johnson MF, and Wilby RL. 2015. Seeing the landscape for the trees: Metrics to guide riparian shade management in river catchments. Water Resources Research 51:3754-3769. DOI: 10.1002/2014WR016802.

Laliberte AS, and Ripple WJ. 2004. Range contractions of North American carnivores and ungulates. BioScience, 54: 123–138. DOI: 10.1641/0006-3568(2004)054[0123:RCONAC]2.0.CO;2

Leroux SJ, Schmiegelow FK, Lessard RB, and Cumming SG. 2007. Minimum dynamic reserves: a framework for determining reserve size in ecosystems structured by large disturbances. Biological Conservation 138:464-473.

Locke H. 2015. Nature needs (at least) half: A necessary new Agenda for protected areas. *In* Protecting the Wild, *Edited by* G Wuerthner, E Crist, and T Butler. Island Press, Washington, DC. pp. 3-15.

McGuire JL, Lawler JJ, MCrae BH, Nuñez TA, and Theobald DM. 2016. Achieving climate connectivity in a fragmented landscape. Proceedings of the National Academy of Sciences, 201602817.

McKenney DW, Hutchinson MF, Papadopol P, Lawrence K, Pedlar J, Campbell K, et al. 2011. Customized spatial climate models for North America. Bulletin of the American Meteorological Society 92:1611-1622. DOI: 10.1175/2011BAMS3132.1.

National Ecological Framework for Canada. 1996. Ecoregions of Canada 1996, [online]: Available from sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.

National Ecological Framework for Canada (NEFC). 1996b. Ecozones of Canada 1996 [online]: Available from sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.

Noss RF, Dobson AP, Baldwin R, Beier P, Davis CR, Dellasala DA, et al. 2012. Bolder thinking for conservation. Conservation Biology 26:1-4.

Rehm EM, Olivas P, Stroud J, and Feeley KJ. 2015. Losing your edge: climate change and the conservation value of range-edge populations. Ecology and Evolution, 5: 4315–4326. PMID: 26664681 DOI: 10.1002/ece3.1645.

Styles D, Börjesson P, d'Hertefeldt T, Birkhofer K, Dauber J, Adams P, et al. 2016. Climate regulation, energy provisioning and water purification: quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. Ambio, 45: 872–884. PMID: 27240661 DOI: 10.1007/s13280-016-0790-9.

Svancara LK, Brannon JR, Scott M, Groves CR, Noss RF, and Pressey RL. 2005. Policy-driven versus evidence-based conservation: a review of political targets and biological needs. Bioscience 55: 989-995.