Velocity-based macrorefugia for boreal passerine birds

DOI: 10.5281/zenodo.1299880

Diana Stralberg, Boreal Avian Modelling Project (diana.stralberg@ualberta.ca)

Climate refugia—areas of species persistence under climate change—may vary in proximity to a species' current distribution, with major implications for their conservation value. Thus, the concept of climate velocity (Loarie et al. 2009)—the speed at which an organisms must migrate to keep pace with climate change— is useful to compare and evaluate refugia. Climate velocity metrics have been used to identify species and ecosystems that are most vulnerable to future climate change, as indicated by high climate velocity (Loarie et al. 2009, Burrows et al. 2011, Serra-Diaz et al. 2014). Using new methods, both forward and backward velocity can be calculated, providing complementary information about patio-temporal responses to climate change (Hamann et al. 2014, Carroll et al. 2015). In particular, backward velocity calculations—and the corresponding distance traveled to reach a given future suitable climate—can be used to identify areas of high potential refugium value for a given time period and species (Stralberg et al. 2018). Velocity-based refugia for a given species represent areas of future climatic suitability that are in close geographic proximity to currently occupied areas, i.e., where chances of rapid colonization (or persistence) in response to climate change is high.

Refugia layers were calculated for 53 forest-associated species (Table 1) based on spatial density models for baseline and projected future climates (Stralberg et al. 2015a, Stralberg et al. 2015b). Mean density estimates within 4-km grid cells were converted to binary estimates of suitable core habitat, defined as the grid cells where the model-predicted density exceeded the mean baseline (1961-1990) predicted density for that species within the study area (Stralberg et al. 2015a), defined here as Brandt's (2009) boreal region of North America. Core habitat predictions were then used to calculate backward biotic velocity (Carroll et al. 2015) for each species, based on four different CMIP3 (Meehl et al. 2007) global climate models (MPI ECHAM5, CCCMA CGCM3.1, GFDL CM2.1, and HadGEM1), two different time periods (2041-2070 and 2071-2100), and a high-end, business-as-usual emissions scenario (SRES A2, IPCC 2001). For each species / climate model / time period combination i, I calculated the distance (d_{ij}) in km from each future distribution pixel j to the nearest current distribution pixel. The assumption was that longer distances (larger backward velocity values) represented lower refugia potential, and the primary objective was to rank refugia potential by distance.

From these distance / time (velocity) layers, I applied the refugia metric described in Stralberg et al. (2018), which uses a non-linear distance decay function to down-weight larger distances, given the low probability of natural dispersal and colonization success. The decay function is based on a fat-tailed dispersal kernel, which accommodates rare long-distance tree dispersal events, and has been invoked to explain the rapid post-glacial recolonization of trees across northern North America at the end of the Late Pleistocene age (Clark et al. 1998). Although birds can disperse much farther and faster due to their ability to fly, we assumed that bird dispersal would be limited by tree dispersal.

The standardized index of refugium potential, R_{ij}, is defined as the negative exponential portion of a fat-tailed dispersal kernel (Clark et al. 1998):

$$R_{ij} = \exp\left(-\left|\frac{d_{ij}}{\alpha}\right|^{c}\right),$$

where $c = 0.5$ (Clark et al. 1998) and $\alpha = 8.333$ (the value resulting in a mean dispersal distance of 50 km per century, based on the first moment of the dispersal kernel). The index has a value of 1 when $d_{ij} = 0$ (i.e., for *in situ* refugia), rapidly declines to a value of 0.09 at 50 km, and then slowly converges toward 0.

For each time period, standardized refugia index values were averaged across the four GCMs to yield an ensemble index for each species. Pixels with no suitable niche space for a given GCM were converted to zero to down-weight their importance in subsequent ensemble calculations.

Two version of a multi-species index were generated: (1) an unweighted simple average across all 53 species, and (2) a version weighted by species' projected distributional responses to climate change, following methods in Stralberg et al. (2018). For the weighted multi-species refugia index, each species' ensemble refugia index was divided by the mean proportional change in total potential distribution area (future/present area) for that species (see Stralberg et al. 2015b) and then averaged across all species. For species with projected future decreases in suitable niche space, proportional change values were truncated at 0.5, yielding a maximum weighted refugia value of 2. For any given species, in both the weighted and unweighted versions, pixels with no suitable niche space during the baseline period or in the future under any of the four GCMs were omitted in the species averaging process so as to prevent the index from being driven primarily by species richness; zero values were assigned where suitable baseline niche space was not projected to be occupied in the future. R code is available on GitHub at https://github.com/dstralberg/Refugia/blob/master/StralbergEtAlGEB2018Macorefugia.Rmd.

The weighted refugia index for 53 boreal songbird species under for the 2041-2070 time period ranged from 0.032 (1st percentile) to 0.779 (99th percentile), with a median of 0.200 and an even distribution (Table 2). The highest weighted refugia values (99th percentile) were located in the mountains of British Columbia and along the Labrador coast; values in the 90th percentile were found throughout western mountains and in northern and eastern Quebec, and Newfoundland and Labrador (Figure 1a). In general, the lowest weighted refugia values (10th percentile) were found in western interior boreal regions. Weighted refugia values were lower for the 2071-2100 time period, ranging from 0.002 to 0.675 (Table 2) but followed similar spatial patterns (Figure 1b). Unweighted refugia index values ranged from 0.006 and 0.001 (1^{st} percentile) to 0.421 and 0.297 (99^{th} percentile) for the 2041-2070 and 2071-2100 time periods, respectively (Table 2, Figure 2). The highest unweighted refugia values were found in central Ontario and Québec, and northern Newfoundland for the 2041-2070 period, but were concentrated mostly along the Labrador coast by the 2071-2100 period.

Refugia layers for individual species, as well as weighted and unweighted multi-species versions are available in raster (geotiff) format on-line through Zenodo (https://doi.org/10.5281/zenodo.1299880), also accessible via AdaptWest (adaptwest.databasin.org) and Boreal Avian Modelling Project (borealbirds.ca) websites.

This report is a contribution of the Boreal Avian Modelling (BAM) Project, an international research collaboration targeting the ecology, management, and conservation of boreal birds. We acknowledge BAM's members, avian and biophysical Data Partners, and funding agencies (including Environment and Climate Change Canada and the U.S. Fish & Wildlife Service), listed in full at www.borealbirds.ca/index.php/acknowledgements.

Suggested citation

Stralberg, D. Velocity-based macrorefugia for boreal passerine birds. Boreal Avian Modelling Project, Edmonton, Alberta, Canada. DOI: 10.5281/zenodo.1299880

References

Brandt, J. P. 2009. The extent of the North American boreal zone. *Environmental Reviews* 17:101–161.

Burrows, M. T., D. S. Schoeman, L. B. Buckley, P. Moore, E. S. Poloczanska, K. M. Brander, C. Brown, J. F. Bruno, C. M. Duarte, B. S. Halpern, J. Holding, C. V. Kappel, W. Kiessling, M. I. O'Connor, J. M. Pandolfi, C. Parmesan, F. B. Schwing, W. J. Sydeman, and A. J. Richardson. 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science* 334:652-655.

Carroll, C., J. J. Lawler, D. R. Roberts, and A. Hamann. 2015. Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. *PLoS ONE* 10:e0140486.

Clark, J. S., C. Fastie, G. Hurtt, S. T. Jackson, C. Johnson, G. A. King, M. Lewis, J. Lynch, S. Pacala, C. Prentice, E. W. Schupp, I. I. I. T. Webb, and P. Wyckoff. 1998. Reid's paradox of rapid plant migration dispersal theory and interpretation of paleoecological records. *BioScience* 48:13-24.

Hamann, A., D. Roberts, Q. Barber, C. Carroll, and S. Nielsen. 2014. Velocity of climate change algorithms for guiding conservation and management. *Global Change Biology* 21:997–1004.

IPCC. 2001. Climate Change 2001. Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The velocity of climate change. *Nature* 462:1052-1055.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor. 2007. The WCRP CMIP3 multi-model dataset: a new era in climate change research. *Bulletin of the American Meteorological Society* 88:1383-1394.

Serra-Diaz, J. M., J. Franklin, M. Ninyerola, F. W. Davis, A. D. Syphard, H. M. Regan, and M. Ikegami. 2014. Bioclimatic velocity: the pace of species exposure to climate change. *Diversity and Distributions* 20:169-180.

Stralberg, D., E. M. Bayne, S. G. Cumming, P. Sólymos, S. J. Song, and F. K. A. Schmiegelow. 2015a. Conservation of future boreal forest bird communities considering lags in

vegetation response to climate change: a modified refugia approach. *Diversity and Distributions* 21:1112-1128.
Stralberg, D., C. Carroll, J. H. Pedlar, C. B. Wilsey, D. W. McKenney, and S. E. Nielsen. 2018. Macrorefugia for North American trees and songbirds: Climatic limiting factors and multi-scale topographic influences. *Global Ecology and Biogeography* 27:690-703.
Stralberg, D., S. M. Matsuoka, A. Hamann, E. M. Bayne, P. Sólymos, F. K. A. Schmiegelow, X. Wang, S. G. Cumming, and S. J. Song. 2015b. Projecting boreal bird responses to climate change: the signal exceeds the noise. *Ecological Applications* 25:52–69.

Table 1. 53 forest-associated species included in refugia index

Code	Species common name (*scientific name*)
AMRE	American Redstart (*Setophaga ruticilla*)
BAWW	Black-and-white Warbler (*Mniotilta varia*)
BBWA	Bay-breasted Warbler (*Setophaga castanea*)
BCCH	Black-capped Chickadee (*Poecile atricapillus*)
BHVI	Blue-headed Vireo (*Vireo solitarius*)
BLWA	Blackburnian Warbler (*Setophaga fusca*)
BLJA	Blue Jay (*Cyanocitta cristata*)
BLPW	Blackpoll Warbler (*Setophaga striata*)
BOCH	Boreal Chickadee (*Poecile hudsonicus*)
BRCR	Brown Creeper (*Certhia americana*)
BTNW	Black-throated Green Warbler (*Setophaga virens*)
CAWA	Canada Warbler (*Cardellina canadensis*)
CEDW	Cedar Waxwing (*Bombycilla cedrorum*)
CMWA	Cape May Warbler (*Setophaga tigrina*)
CONW	Connecticut Warbler (*Oporornis agilis*)
CORA	Common Raven (*Corvus corax*)
CORE	Common Redpoll (*Acanthis flammea)*
DEJU	Dark-eyed Junco (*Junco hyemalis*)
EVGR	Evening Grosbeak (*Coccothraustes vespertinus*)
FOSP	Fox Sparrow (*Passerella iliaca*)
GCKI	Golden-crowned Kinglet (*Regulus satrapa*)
GCTH	Gray-cheeked Thrush (*Catharus minimus*)
GRAJ	Gray Jay (*Perisoreus canadensis*)
HETH	Hermit Thrush (*Catharus guttatus*)
LEFL	Least Flycatcher (*Empidonax minimus*)
MAWA	Magnolia Warbler (*Setophaga magnolia*)
MOWA	Mourning Warbler (*Geothlypis philadelphia*)
NAWA	Nashville Warbler (*Oreothlypis ruficapilla*)
NOWA	Northern Waterthrush (*Parkesia noveboracensis*)

Code	Species common name (*scientific name*)
OCWA	Orange-crowned Warbler (*Oreothlypis celata*)
OSFL	Olive-sided Flycatcher (*Contopus cooperi*)
OVEN	Ovenbird (*Seiurus aurocapilla*)
PAWA	Palm Warbler (*Setophaga palmarum*)
PHVI	Philadelphia Vireo (*Vireo philadelphicus*)
PIGR	Pine Grosbeak (*Pinicola enucleator*)
PISI	Pine Siskin (*Spinus pinus*)
PUFI	Purple Finch (*Carpodacus purpureus*)
RBGR	Rose-breasted Grosbeak (*Pheucticus ludovicianus*)
RBNU	Red-breasted Nuthatch (*Sitta canadensis*)
RCKI	Ruby-crowned Kinglet (*Regulus calendula*)
REVI	Red-eyed Vireo (*Vireo olivaceus*)
RUBL	Rusty Blackbird (*Euphagus carolinus*)
SWTH	Swainson's Thrush (*Catharus ustulatus*)
TEWA	Tennessee Warbler (*Oreothlypis peregrina*)
VATH	Varied Thrush (*Ixoreus naevius*)
WETA	Western Tanager (*Piranga ludoviciana*)
WEWP	Western Wood-Pewee (*Contopus sordidulus*)
WIWA	Wilson's Warbler (*Cardellina pusilla*)
WIWR	Winter Wren (*Troglodytes hiemalis*)
WTSP	White-throated Sparrow (*Zonotrichia albicollis*)
WWCR	White-winged Crossbill (*Loxia leucoptera*)
YBFL	Yellow-bellied Flycatcher (*Empidonax flaviventris*)
YRWA	Yellow-rumped Warbler (*Setophaga coronata*)

Table 2. Percentile values of velocity-based multi-species refugia indices for 53 boreal-breeding songbird species.

	1%	10%	25%	50%	75%	90%	99%
2050s, weighted	0.032	0.243	0.317	0.399	0.484	0.589	0.779
2080s, weighted	0.002	0.090	0.137	0.200	0.281	0.386	0.675
2050s, unweighted	0.006	0.108	0.159	0.218	0.292	0.358	0.421
2080s, unweighted	0.001	0.055	0.083	0.123	0.185	0.241	0.297

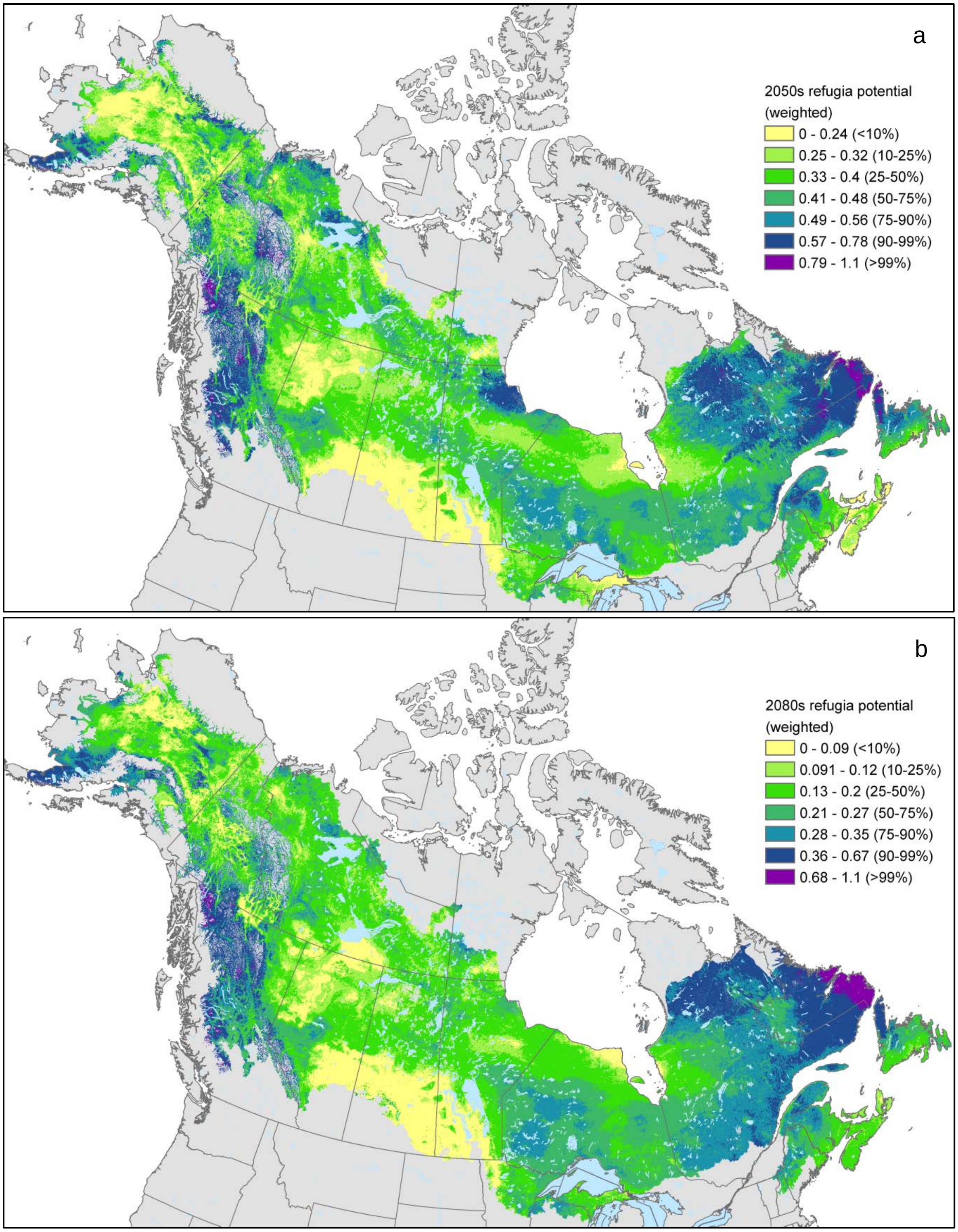

Figure 1. Multi-species refugia indices for (a) 2041-2070 and (b) 2071-2100, averaged across 53 forest-associated boreal-breeding species, weighted by species' projected distributional responses to climate change and mapped by percentiles. Areas covered in rock or snow/ice according to 30-m 2010 North American landcover data have been masked out.

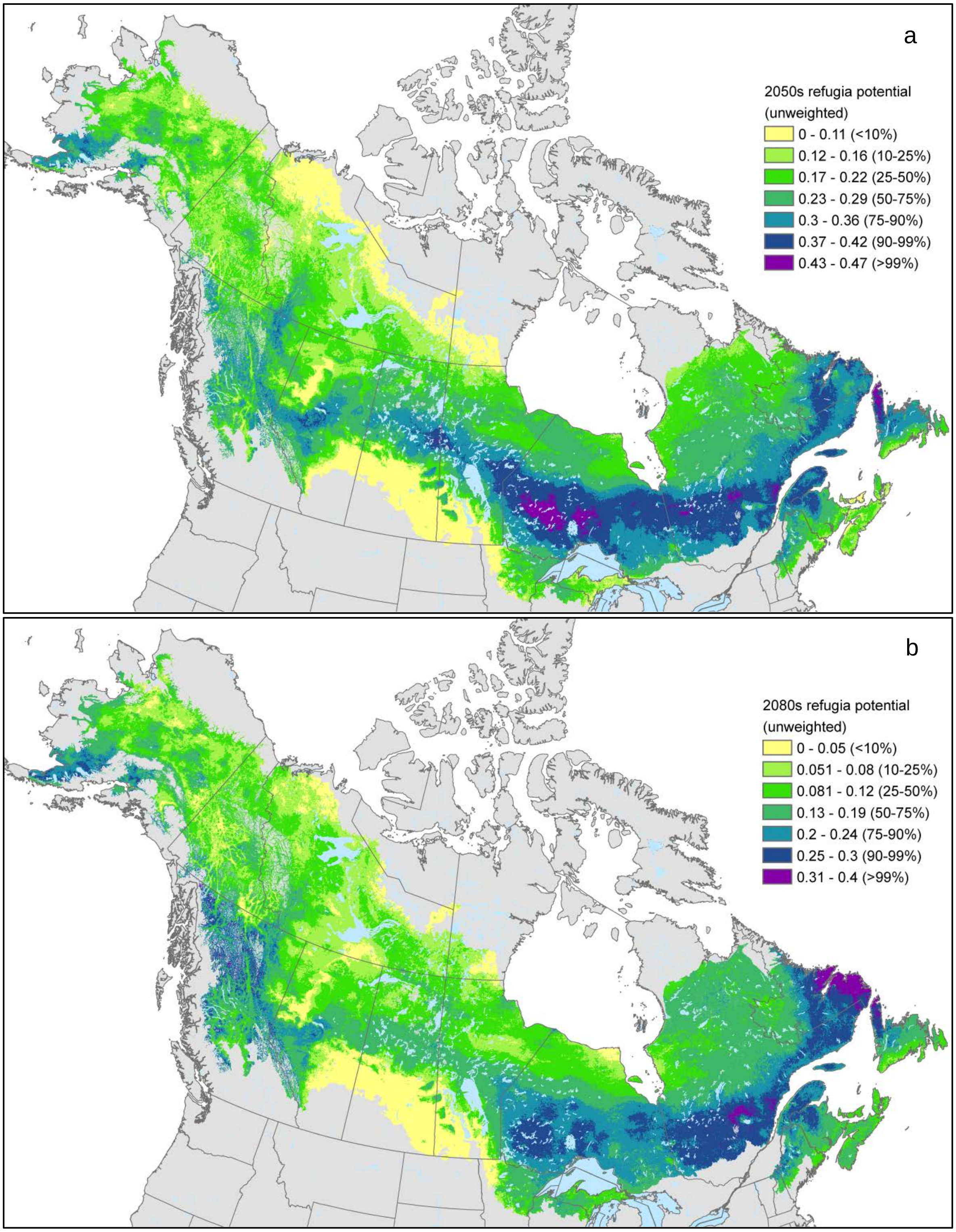

Figure 2. Multi-species refugia indices for (a) 2041-2070 and (b) 2071-2100, averaged across 53 forest-associated boreal-breeding species mapped by percentiles. Areas covered in rock or snow/ice according to 30-m 2010 North American landcover data have been masked out.