Supplementary material for "Comparison and Parallel Implementation of Alternative Moving-Window Metrics of the Connectivity of Protected Areas Across Large Landscapes"

Landscape Ecology

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Acronym, variable and parameter definitions

Table S1: Variable and parameter definitions.

Variable or Parameter	**Description**	**Value**
i,j	Location indices for each pixel or raster cell.	1 to number of cells.
H_i^F, H_i^N	Habitat quality at location *i* with and without the human footprint, respectively (Fig. 1). *F/N* superscripts are omitted where statements apply to both versions.	0 to 1
C_i^F, C_i^N	Unscaled movement cost at location *i* with and without the human footprint, respectively (Pither et al. in review).	0 to 1000
w	Raster cell resolution.	300 metres
c_i	Scaled movement cost at location *i* (eq 2, Table 2).	1 to 20
c_{min}	Minimum movement cost (eq 2, Table 2).	1
c_{max}	Maximum movement cost varies between high and low contrast metric variants (eq 2, Table 2).	1, 2, or 20.
d_{ij}	Distance between location *i* and location *j*. For PARC, distance is measured in scaled cost units (eq 2). Otherwise, distance is Euclidean.	0 to map dimension in metres or scaled cost.
μ	Mean displacement.	2, 5, 10, 20 or 40 km
α	Exponential spatial scale parameter (eqs 1, 3, 4).	$2/\mu$
P_i	PARC connectivity metric (eq 1, Table 2, Fig. 2).	0 to 1
I_i	Beyer's Ecosystem Intactness Index (eq 3, Table 2, Figs 4 and 6).	0 to 1
z	Scaling exponent in Beyer's Ecosystem Intactness Index (eq 3).	0.5
E_i	Simple Euclidean exponential distance-weighted sum metric (eq 4, Figs 4 and 6).	0 to 1
U_i	Simple Euclidean uniform distance-weighted sum metric (eq 5).	0 to 1
r	Radius of a circle (eq 5).	$3\mu/2$
t	Timestep	40,250,1000,4001 or 16007
$B_{i,t}$	SAMC B disperser distribution at location *i* and time *t* (eq 6, Table 2, Figs 2, 4, 6).	0 to 1
$M_{i,t}$	SAMC M disperser distribution at location *i* and time *t* with constant movement cost (Table 2, Figs 2, 4, 6).	0 to 1
$R_{i,t}$	SAMC R disperser distribution at location *i* and time *t* with constant mortality (Table 2, Fig 2).	0 to 1
m_i	Mortality at location *i* (eq 7, Table 2).	0.00001 to 1/15

m_{min}	Minimum mortality (eq 7, Table 2).	0.00001
m_{max}	Maximum mortality varies between high and low contrast metric variants (eq 7, Table 2).	0.00001, 1/150, or 1/15.

Table S2: Acronym definitions.

Acronym	**Definition**
CBD	Convention on Biological Diversity
BEII	Beyer's Ecosystem Intactness Index (Beyer et al. 2020).
PARC	Protected Area Representativeness and Connectedness index (Drielsma et al. 2007; Biodiversity Indicators Partnership 2019).
ProtConn	Protected Connected index (Saura et al. 2017).
SAMC	Spatial Absorbing Markov Chain (Fletcher et al. 2019).
DWS	Distance-weighted sum

Derivation of cost and quality layers

Table S3: Cost and quality values for each land type. The highest cost from among the 27 land features was assigned to each pixel *i*. Quality is defined as $H_i = 1 - C_i/1000$. Additional information about the source of each land feature layer and method for assigning costs to land features is provided by Pither et al. (in review).

LAND FEATURE	COST C_i^F / C_i^N	QUALITY H_i^F / H_i^N
CHF - Built environments	1000 / 0	0 / 1
CHF - Croplands	100 / 0	0.9 / 1
CHF - Dams	1000 / 0	0 / 1
CHF - Forestry (cut between 1985 & 2015)	10 / 0	0.99 / 1
CHF - Mining	1000 / 0	0 / 1
CHF - Nighttime lights	1000 / 0	0 / 1
CHF - Oil and gas	1000 / 0	0 / 1
CHF - Pasturelands	10 / 0	0.99 / 1
Lakes >= 10ha	1000 / 1000	0 / 0
Rails	1000 / 0	0 / 0
Roads - minor	10 / 0	0.99 / 1
Roads - two-lane highway	100 / 0	0.9 / 1
Roads - multi-lane highways	1000 / 0	0 / 1
Elevation > 2300m	1000 / 1000	0 / 0
Glaciers	1000 / 1000	0 / 0
Ocean	1000 / 1000	0 / 0
Rivers > 28m3/sec	1000 / 1000	0 / 0
Sea Ice	10 / 10	0.99 / 0.99
Slopes > 30 degrees	1000 / 1000	0 / 0
GHF - Built environments	1000 / 0	0 / 1
GHF - Croplands	100 / 0	0.9 / 1
GHF - Nightime lights	1000 / 0	0 / 1
GHF - Pasturelands	10 / 0	0.99 / 1
GHF - Rails	1000 / 0	0 / 1
GHF - Road buffer (500 - 1000m)	1 / 0	0.999 / 1
GHF - Road buffer (500m)	100 / 0	0.9 / 1
GHF - Roads	1000 / 0	0 / 1

Kernel Shapes and Displacement Patterns

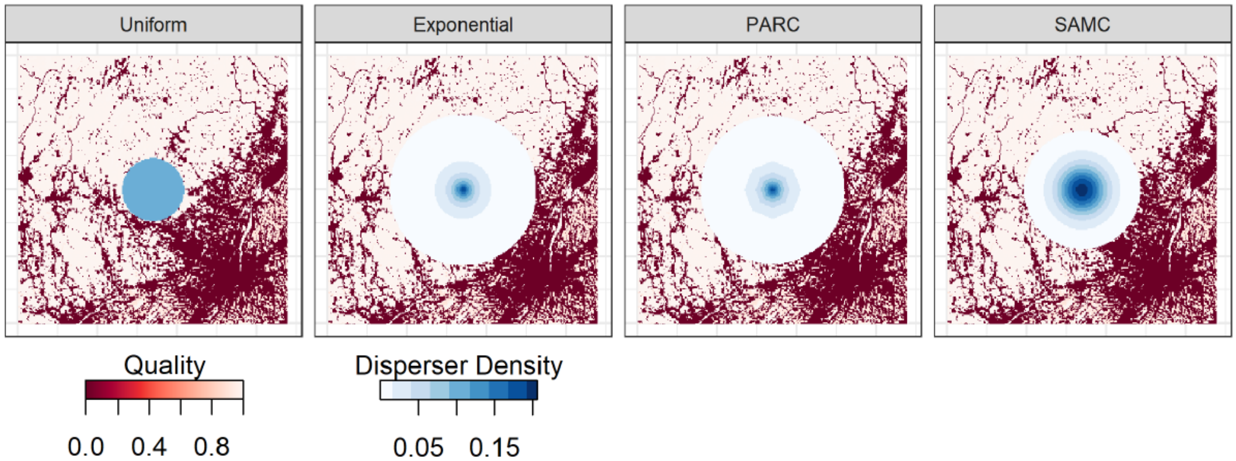

Fig S1. Comparison of kernel shapes and displacement patterns. Blue circles show density of dispersers from a single central location. Mean displacement μ in all cases is 20 km, and habitat quality (green) around Mt. Tremblant (Qc., Canada; Fig 1) is shown for context. The uniform kernel is more compact than the exponential kernel. If cost is uniform, the PARC octagonal least-cost path displacement pattern (with modified 8 cell neighbourhood) is similar to the circular exponential displacement pattern. A SAMC model (with constant mortality = 0.00001, movement cost = 1) calibrated to give mean displacement of 20 km shows a displacement pattern intermediate between the uniform and exponential kernel shapes.

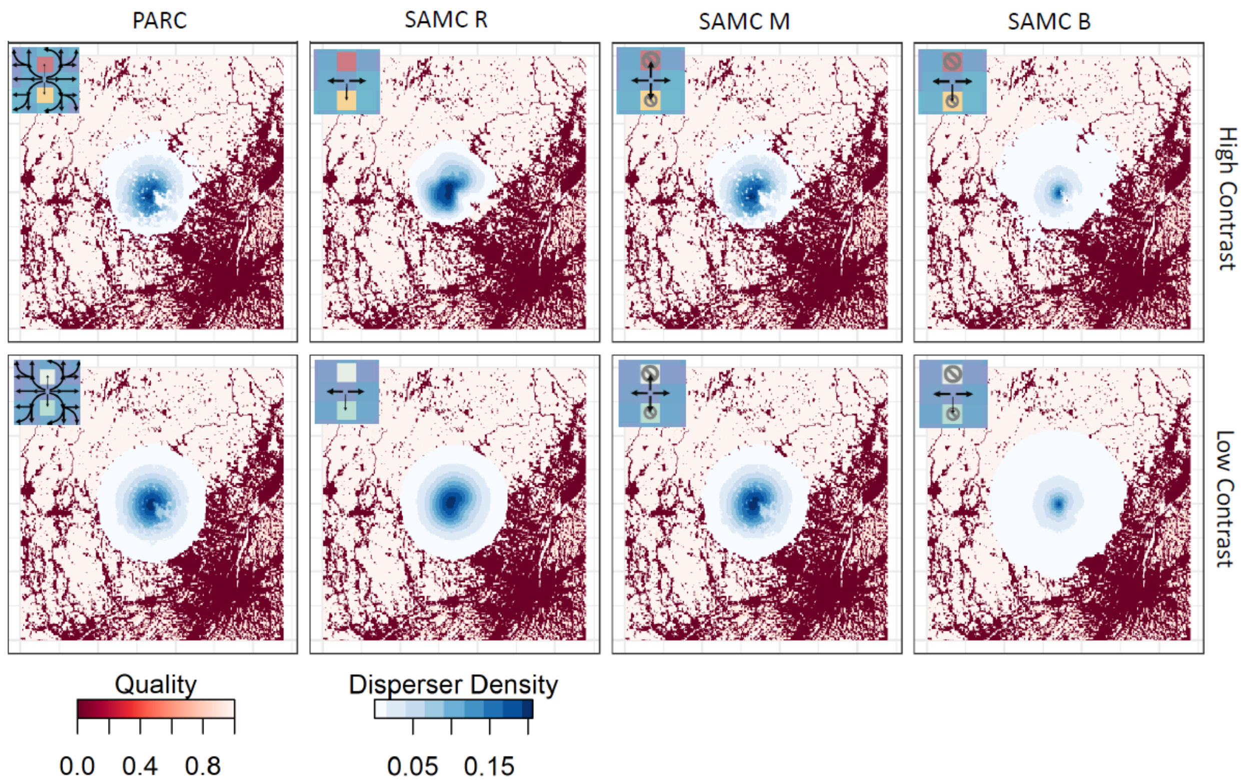

Fig S2. Displacement patterns for PARC and SAMC metric variants (Table 2).

Performance of Parallel Implementations

For performance testing, habitat quality was derived from a global 1 km resolution human modification layer (Kennedy et al. 2019). In addition to the full analysis of Canada (5012 km by 5774 km), tests were run on a set of smaller square subset maps of various widths: 1000 km, 500 km, and 100 km. At least five iterations of each scenario were run on AWS C5 instances with 8/48 CPUs and 16/96 GB of memory. Benchmarking code is available at https://github.com/LandSciTech/LSTD-Connectivity-Paper/blob/main/scripts/x_samc_terra_raster_compare.R.

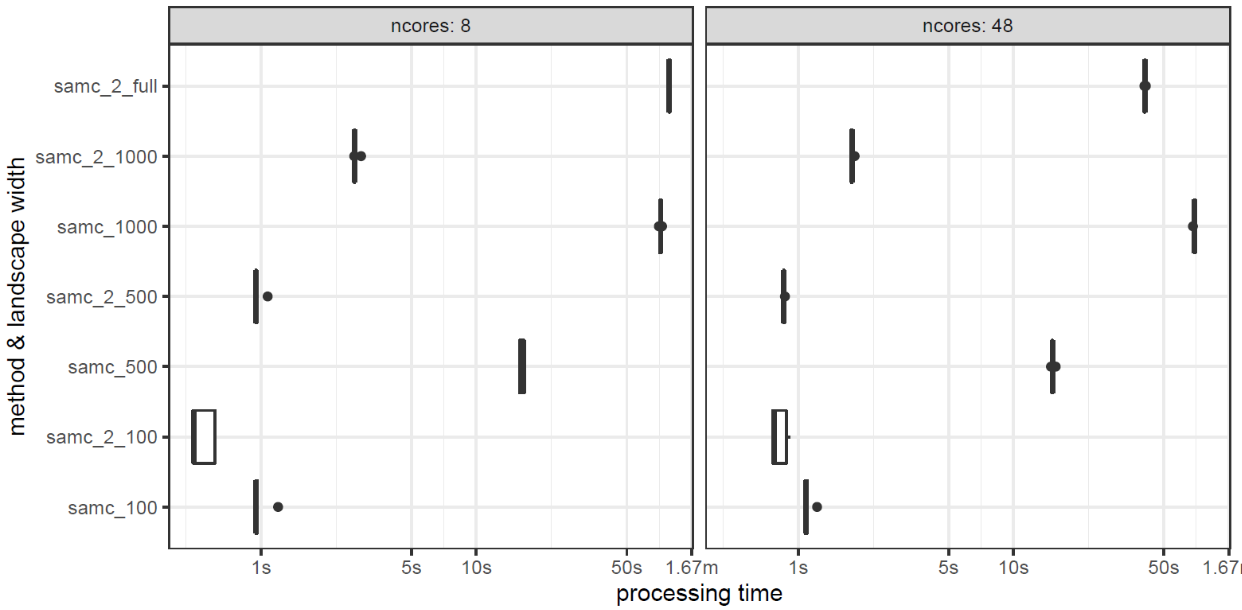

Fig S3. Comparison of processing time for calculation of SAMC unconditional short-term disperser distribution (eq. 6) using our iterative parallel-moving window algorithm (samc_2; https://landscitech.github.io/LSTDConnect/) or the *samc* R package method (Marx et al. 2020), assuming 1000 timesteps. Tests were run on the full map of Canada and subset landscapes of various widths (1000 km, 500 km, 100 km). The advantage of the parallel implementation (samc_2) increases with the number of cores (ncores) and landscape size. Boxplots show variability among test iterations.

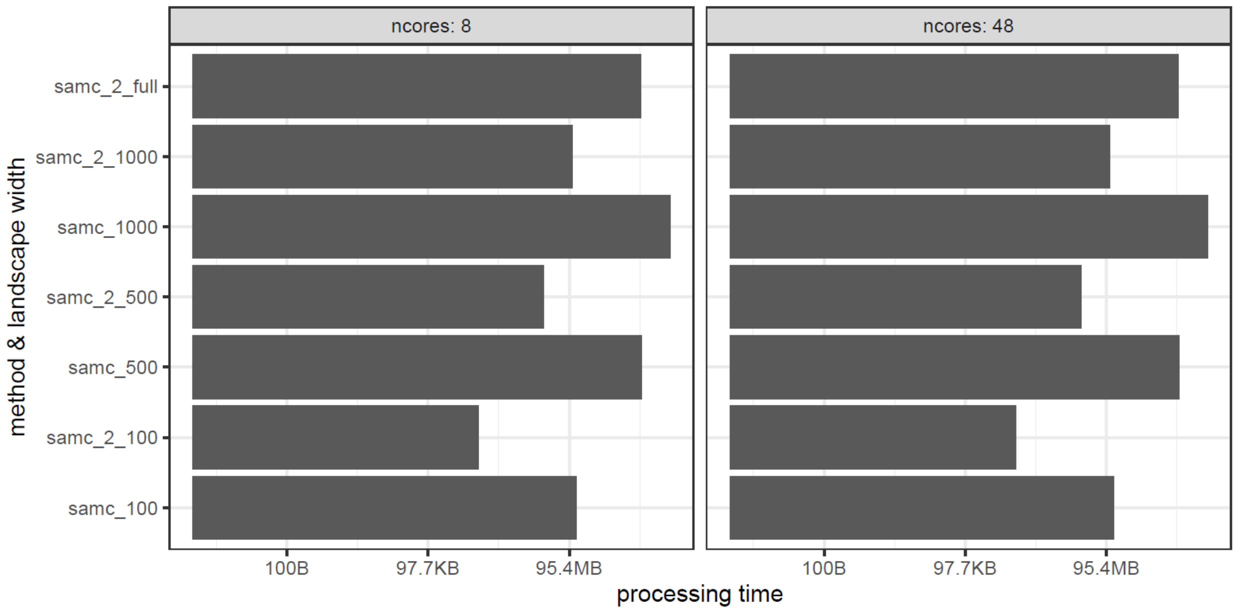

Fig S4. Comparison of memory requirements for calculation of SAMC unconditional short-term disperser distribution (eq. 6) using our iterative parallel moving-window algorithm (samc_2; https://landscitech.github.io/LSTDConnect/) or the *samc* R package method (Marx et al. 2020), assuming 1000 timesteps. Tests were run on the full map of Canada and subset landscapes of various widths (1000 km, 500 km, 100 km). The advantage of our algorithm (samc_2) increases with landscape size.

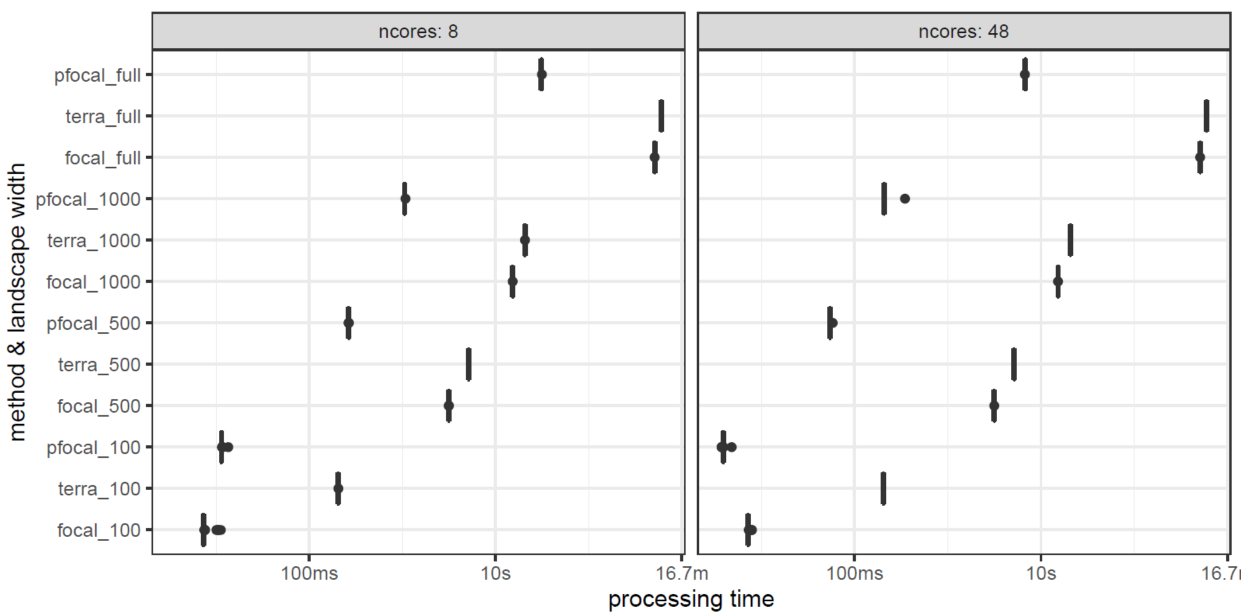

Fig S5. Comparison of processing time for *pfocal* (https://landscitech.github.io/pfocal/), *terra::focal* (Hijmans 2022a), and *raster::focal* (Hijmans 2022b) methods of calculating an exponential distance-weighted sum metric (eq. 4), assuming 10 km mean displacement. Tests were run on the full map of Canada and subset landscapes of various widths (1000 km, 500 km, 100 km). The advantage of parallel processing (*pfocal)* increases with the number of cores (ncores). Boxplots show variability among test iterations.

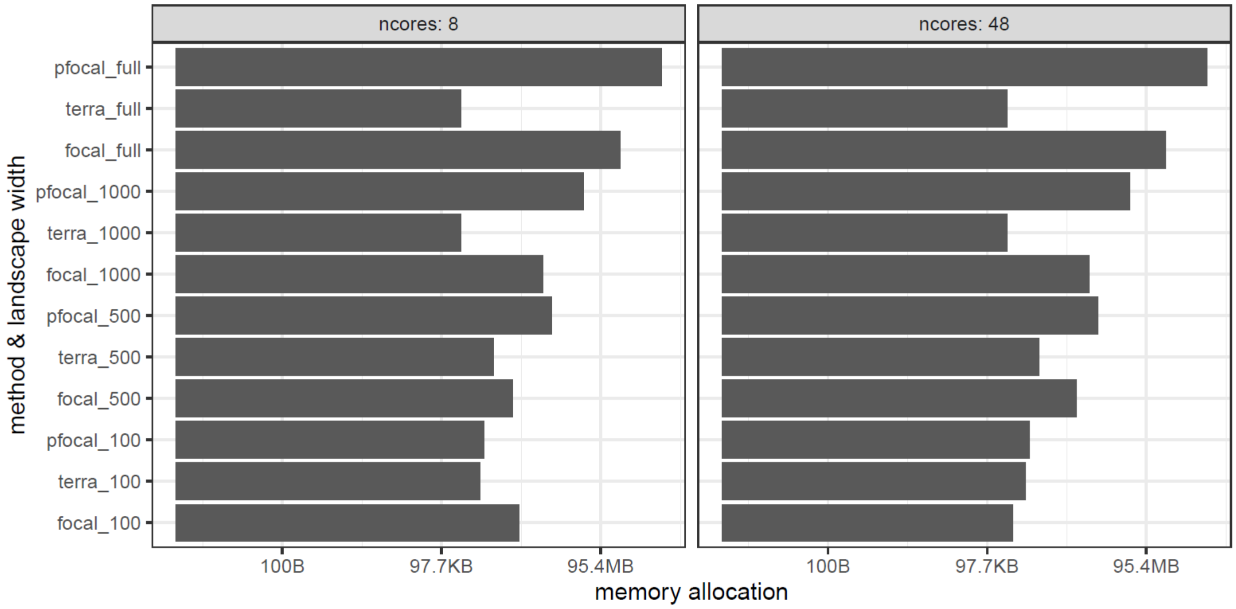

Fig S6. Comparison of memory requirements for *pfocal* (https://landscitech.github.io/pfocal/), *terra::focal* (Hijmans 2022a), and *raster::focal* (Hijmans 2022b) methods of calculating an exponential distance-weighted sum metric (eq. 4), assuming 10 km mean displacement. Tests were run on the full map of Canada and subset landscapes of various widths (1000 km, 500 km, 100 km).

PARC Analysis For a Subset of Protected Areas

We compared PARC, Euclidean distance-weighted sum and SAMC metric variants for a stratified random sample of protected areas across the country by randomly selecting eight protected areas along with the largest and smallest protected area from each of the 15 terrestrial ecozones (Agriculture and Agri-Food Canada 2014). For one of the ecozones, all 9 protected areas (larger than 1 km^2) were included for a total of 149 protected areas. For this subset analysis, habitat quality was derived from a global 1 km resolution human modification layer (Kennedy et al. 2019). PARC metrics are highly correlated with Euclidean distance-weighted sum and SAMC M metrics at each mean displacement level (Figure S3).

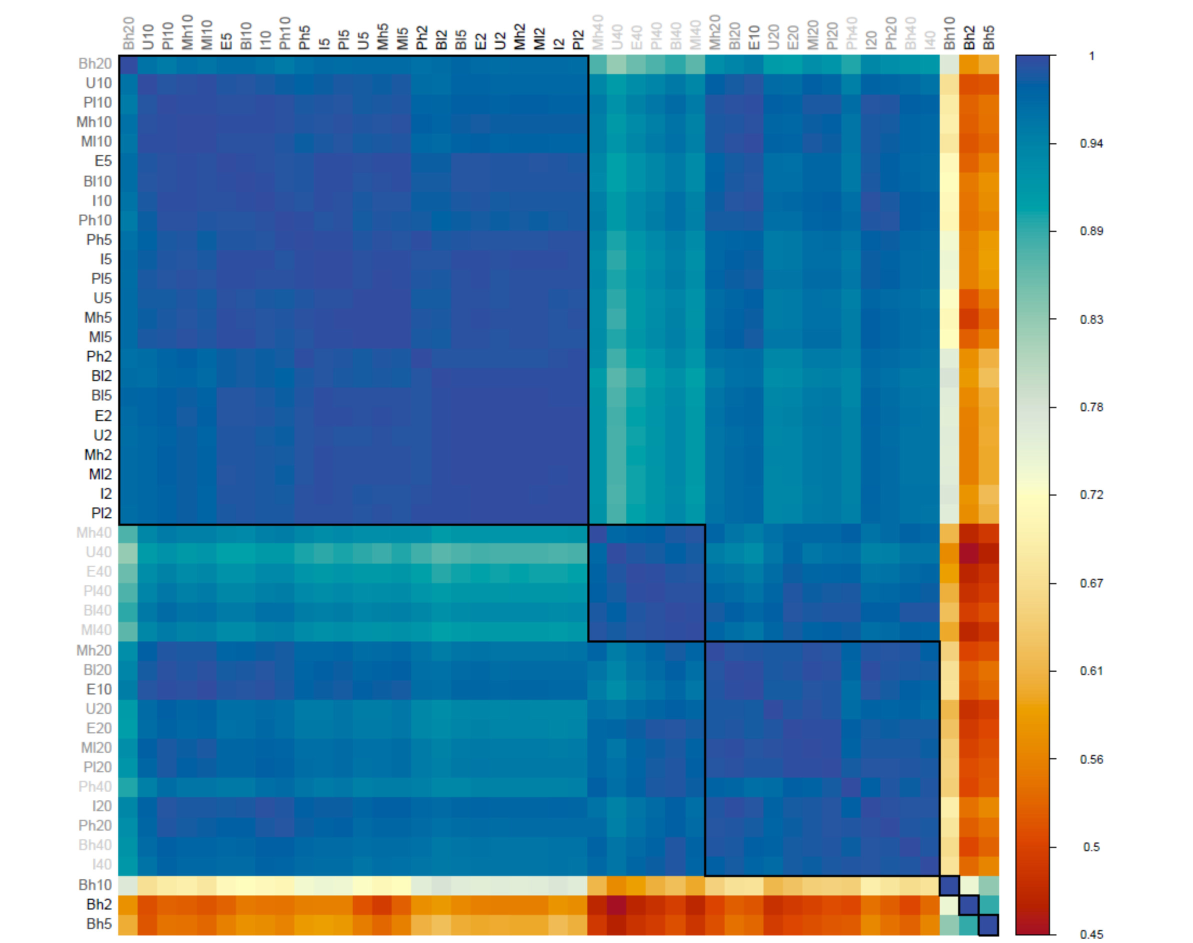

Fig S7. Spearman rank correlations among distance-weighted sum and SAMC metric variants (including PARC) (defined in Table 2) for habitat quality derived from Kennedy et al. (2019) and a subset of 149 protected areas.

Raw and Ratio Metric Values Across Canada

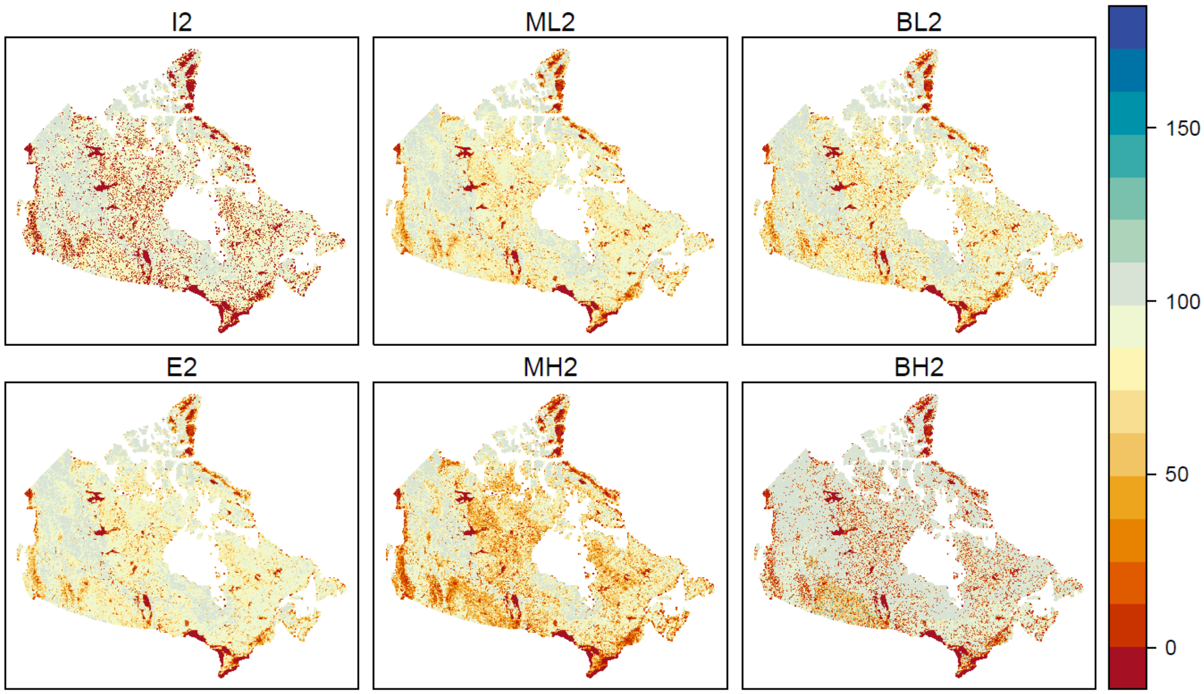

Fig S8. Selected raw metric variants across Canada, assuming 2 km mean displacement.

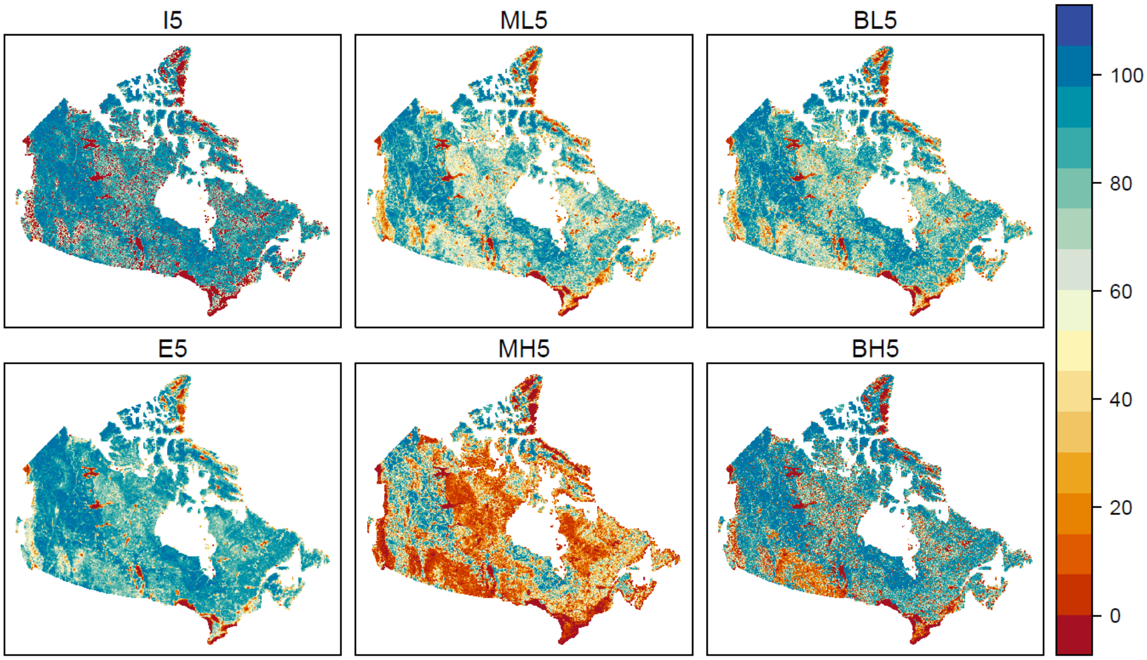

Fig S9. Selected raw metric variants across Canada, assuming 5 km mean displacement.

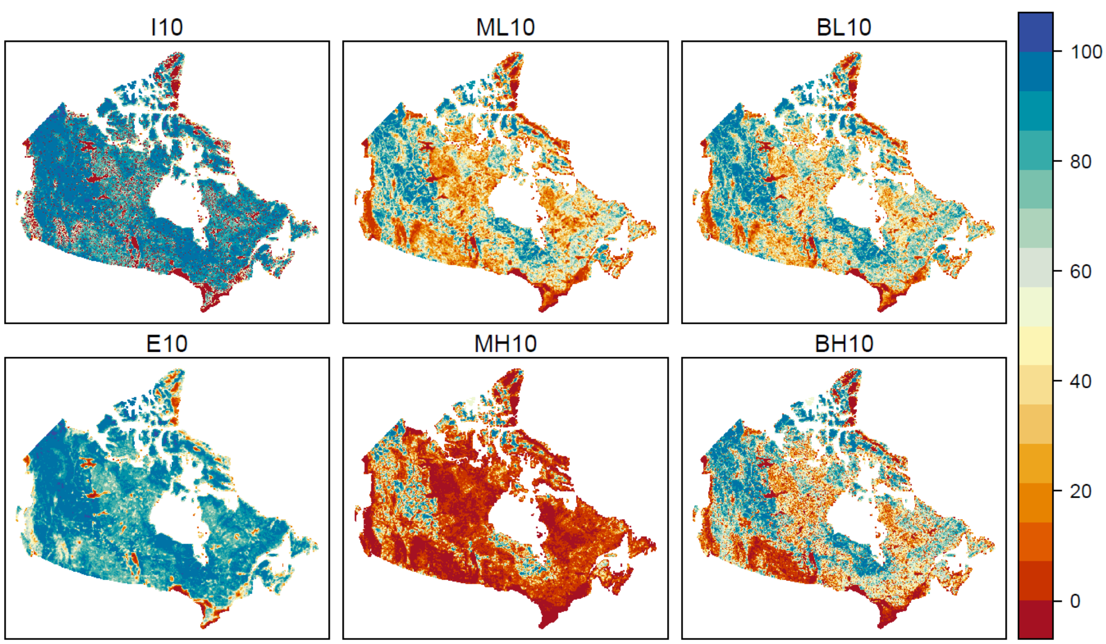

Fig S10. Selected raw metric variants across Canada, assuming 10 km mean displacement.

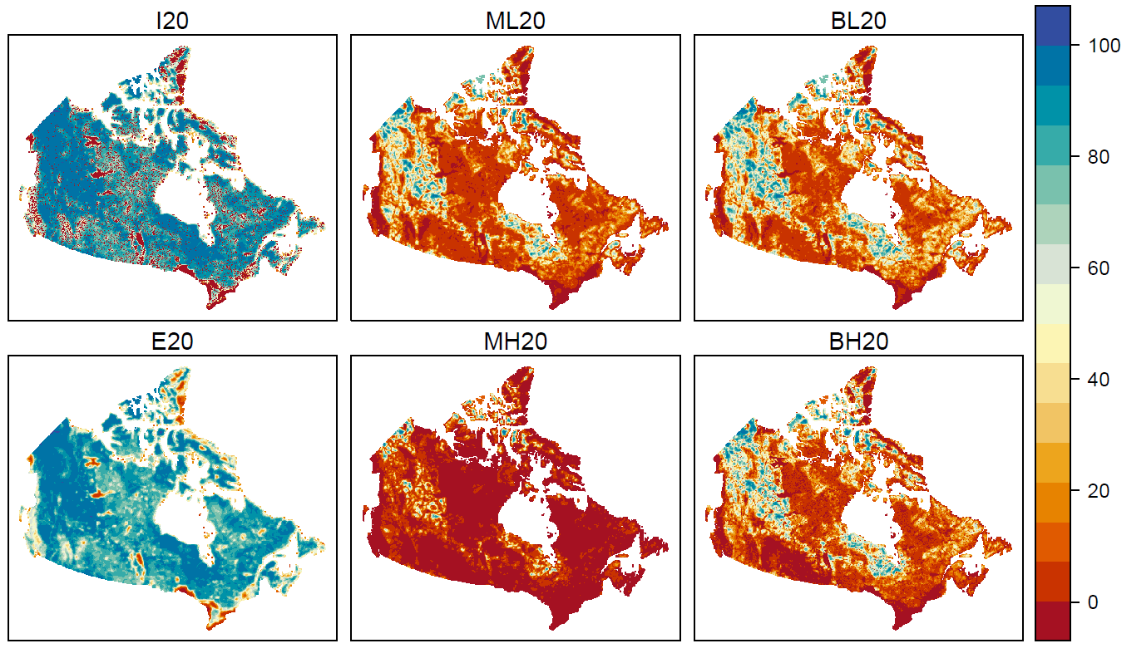

Fig S11. Selected raw metric variants across Canada, assuming 20 km mean displacement.

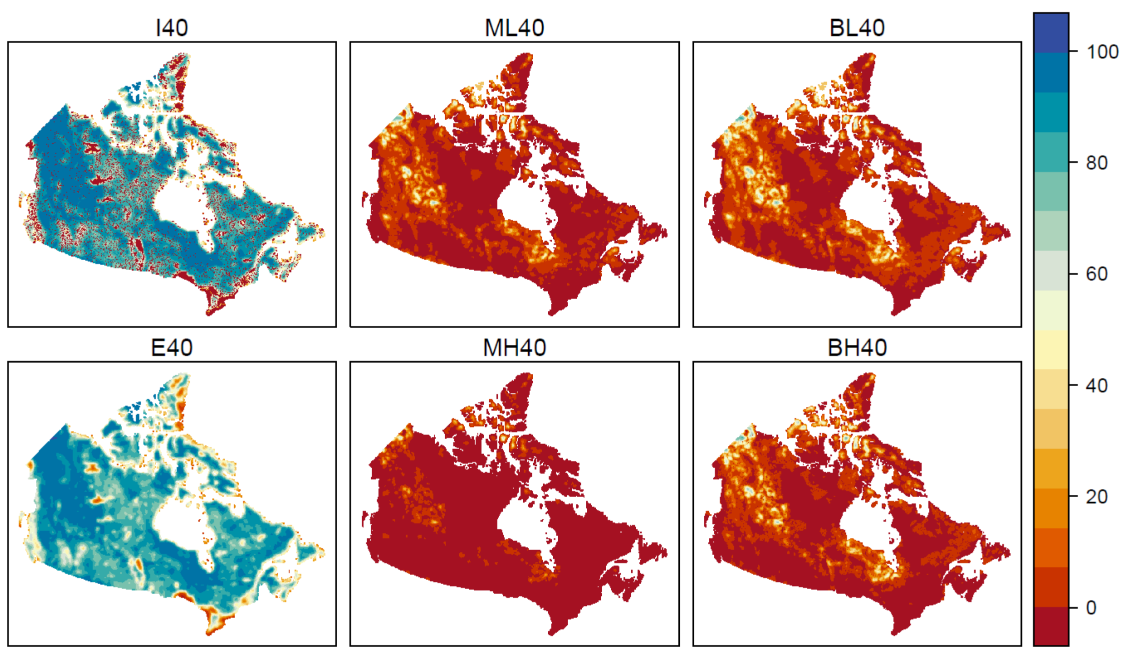

Fig S12. Selected raw metric variants across Canada, assuming 40 km mean displacement.

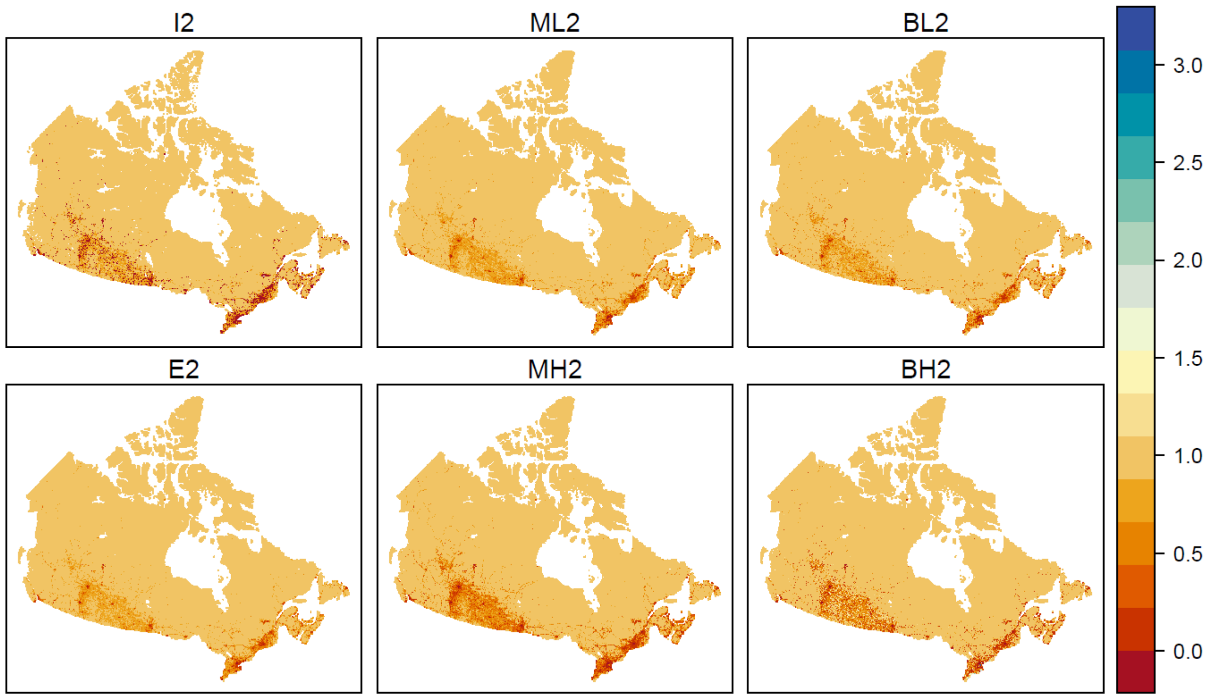

Fig S13. Selected ratio metric variants across Canada, assuming 2km mean displacement.

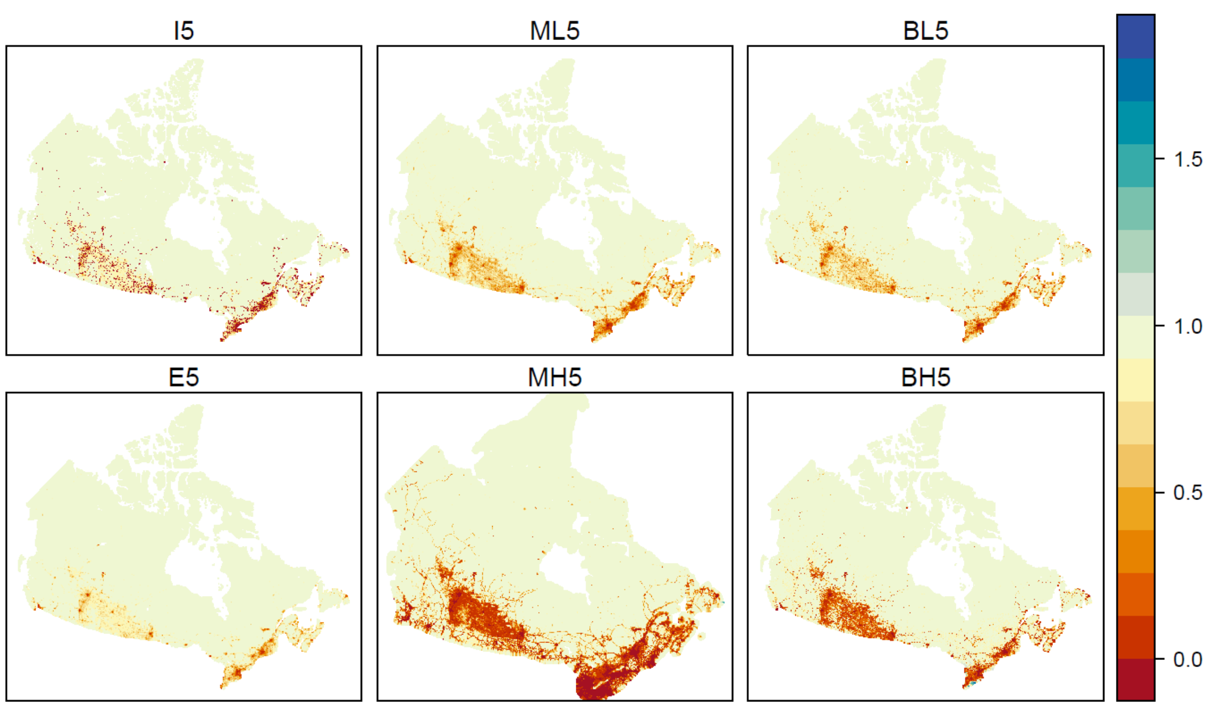

Fig S14. Selected ratio metric variants across Canada, assuming 5km mean displacement.

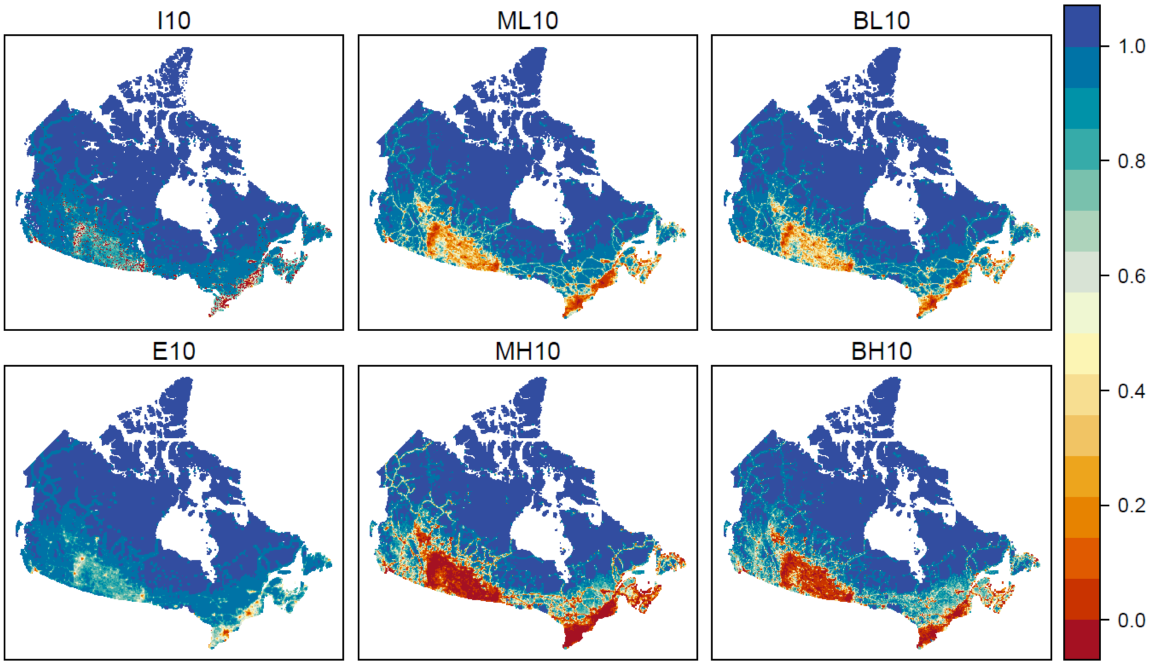

Fig S15. Selected ratio metric variants across Canada, assuming 10 km mean displacement.

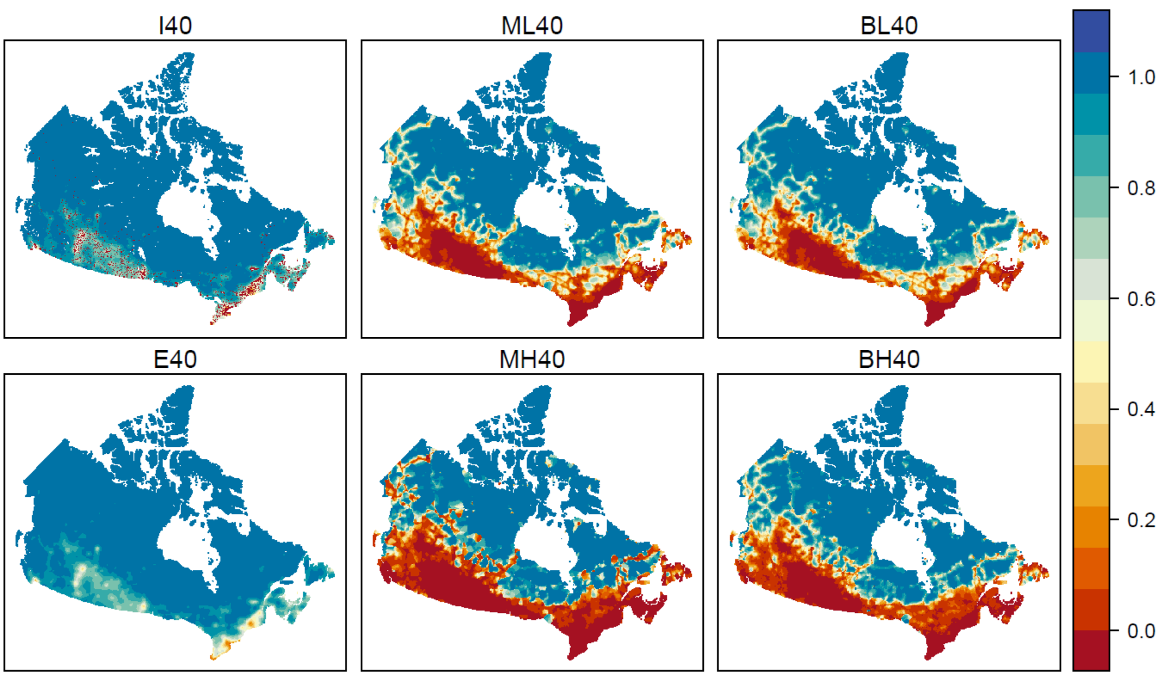

Fig S16. Selected ratio metric variants across Canada, assuming 40 km mean displacement.

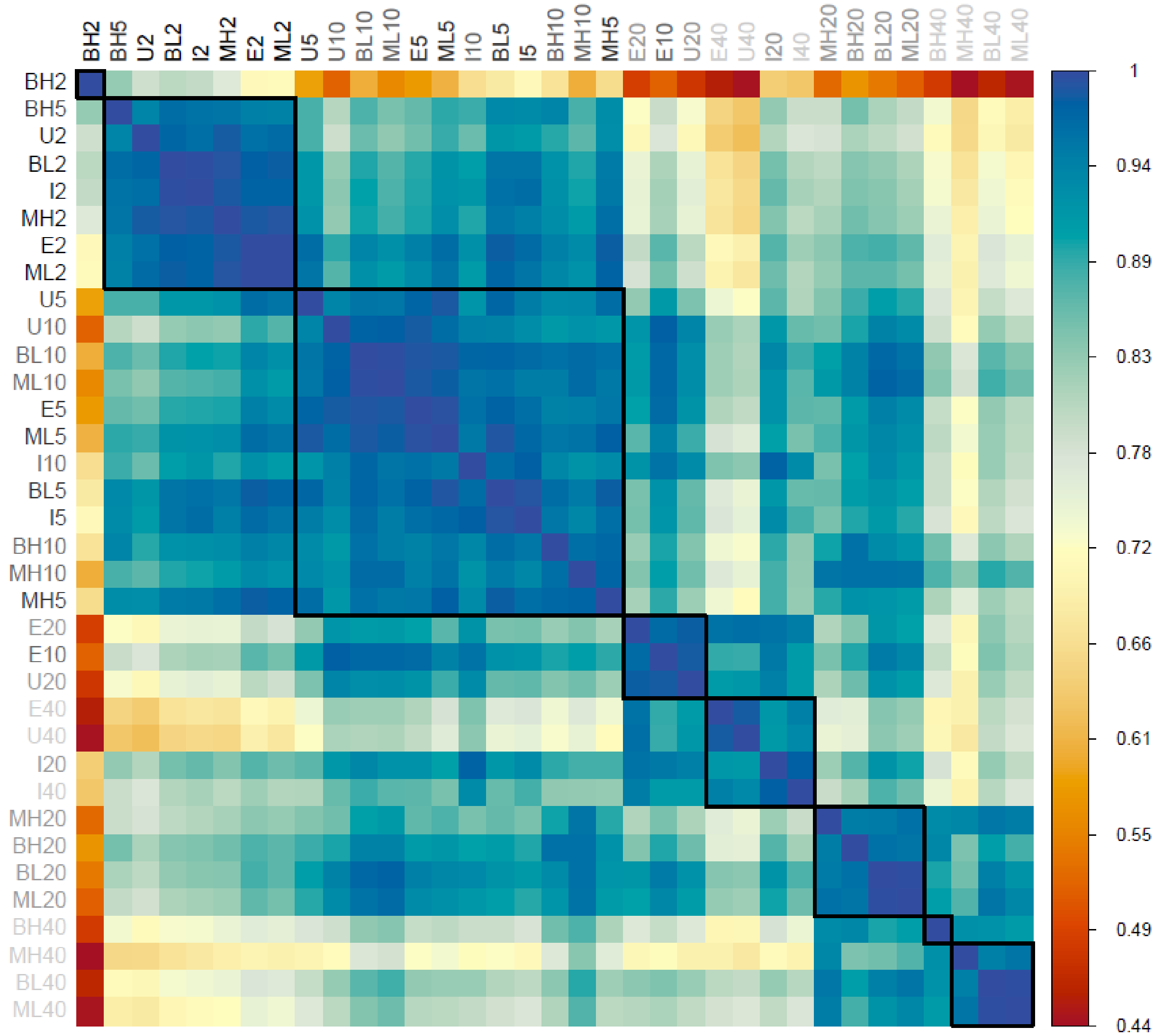

Fig S17. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Atlantic Maritime ecozone.

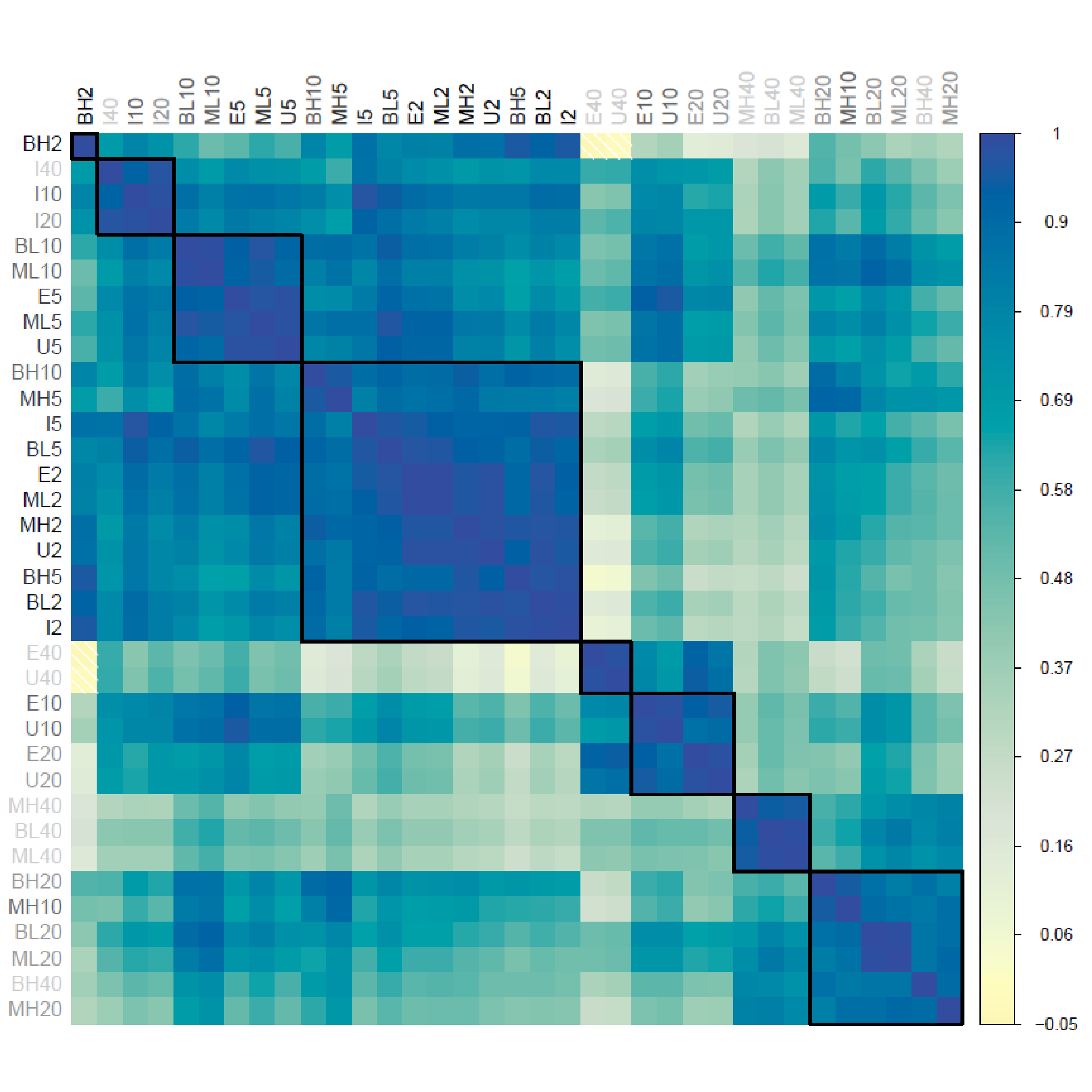

Fig S18. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Pacific Maritime ecozone.

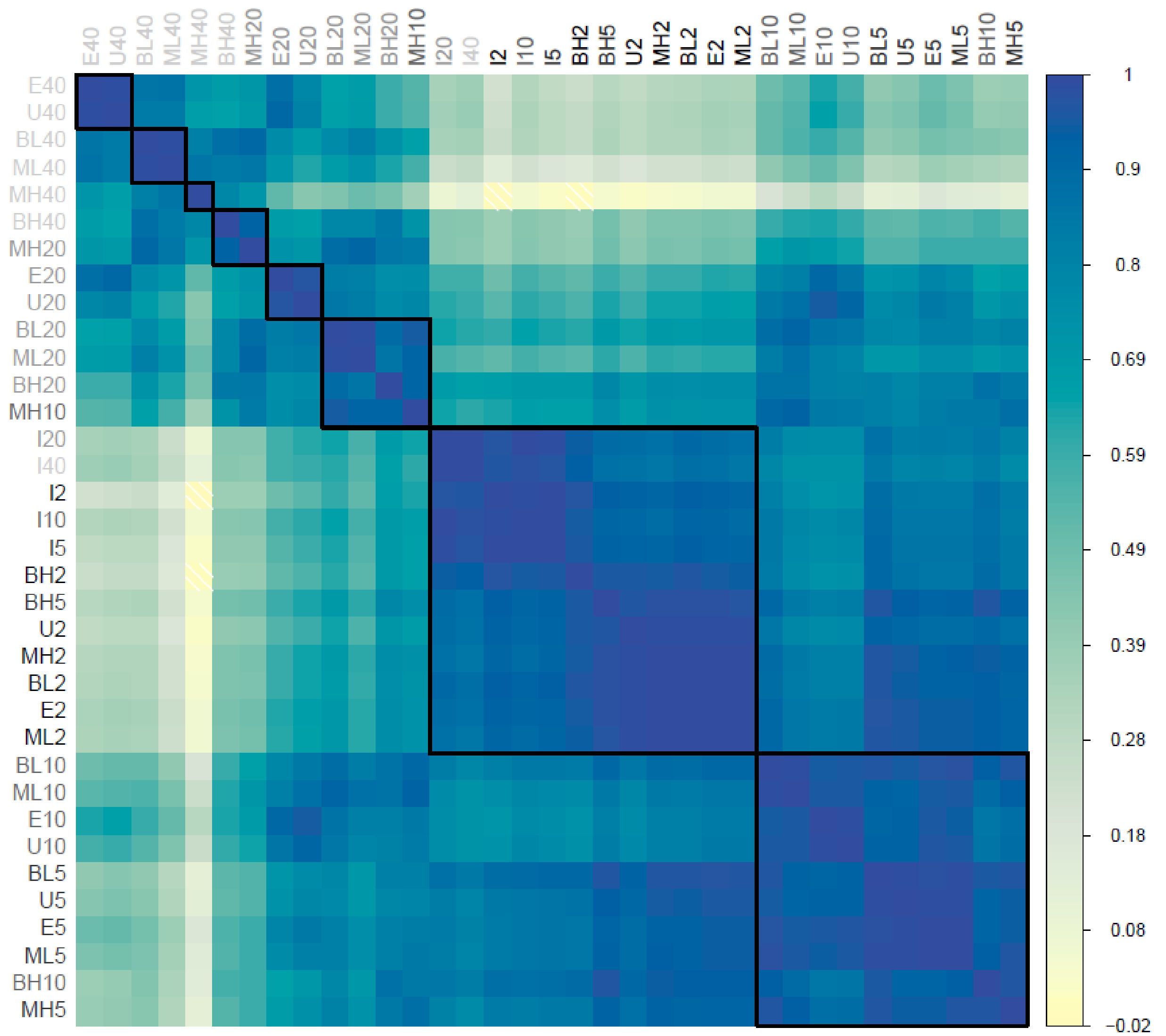

Fig S19. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Mixedwood Plains ecozone.

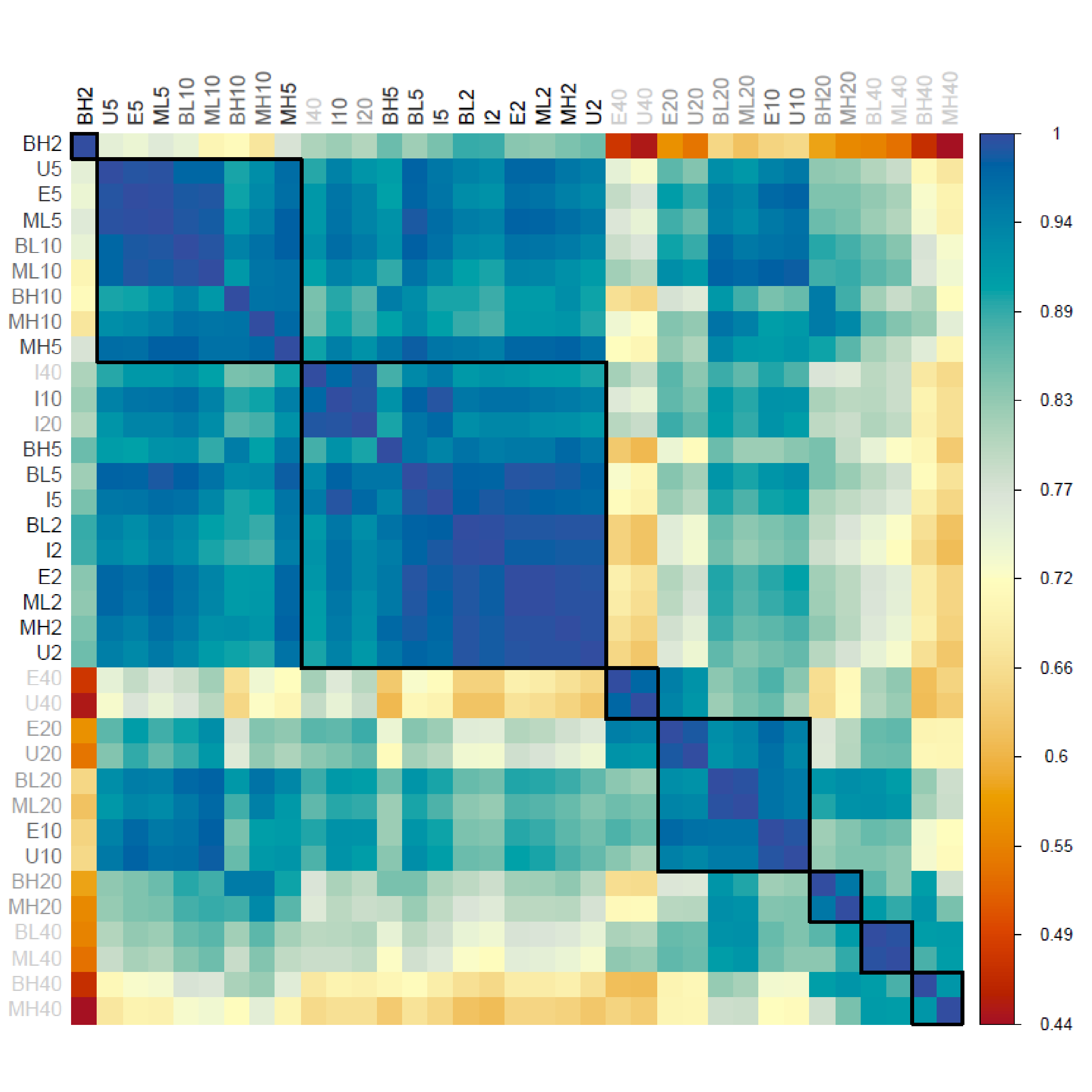

Fig S20. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Prairies ecozone.

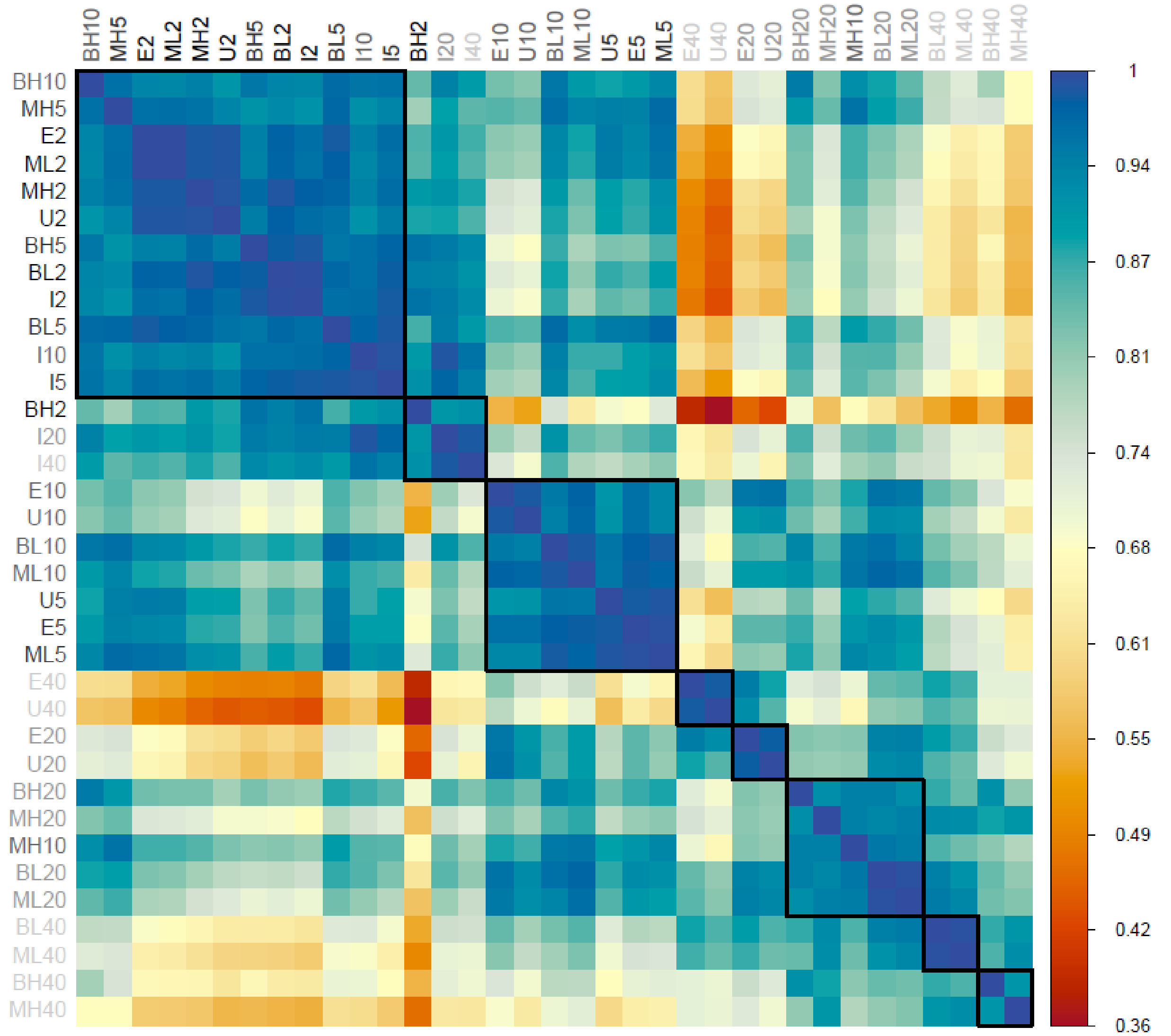

Fig S21. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Montane Cordillera ecozone.

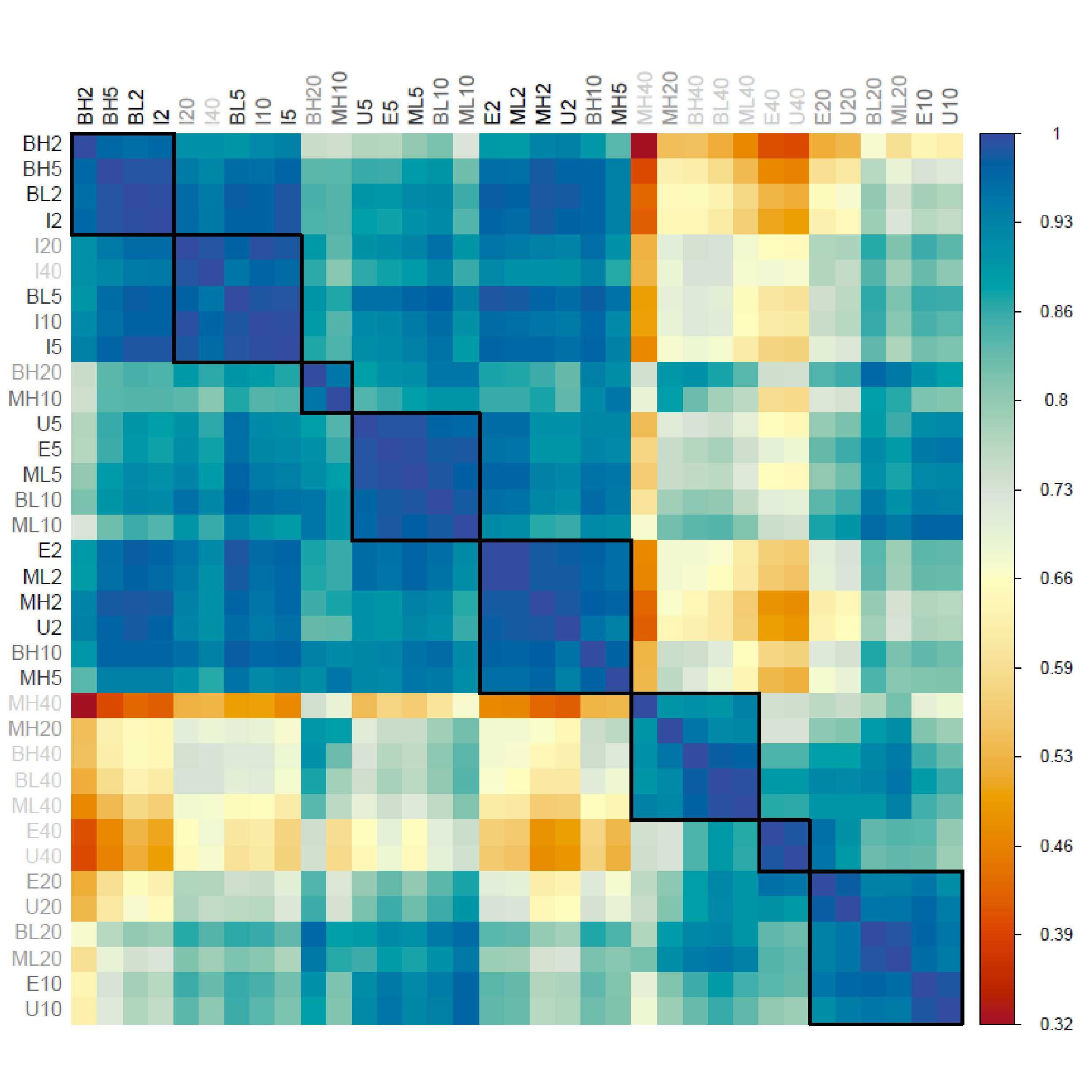

Fig S22. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Boreal Cordillera ecozone.

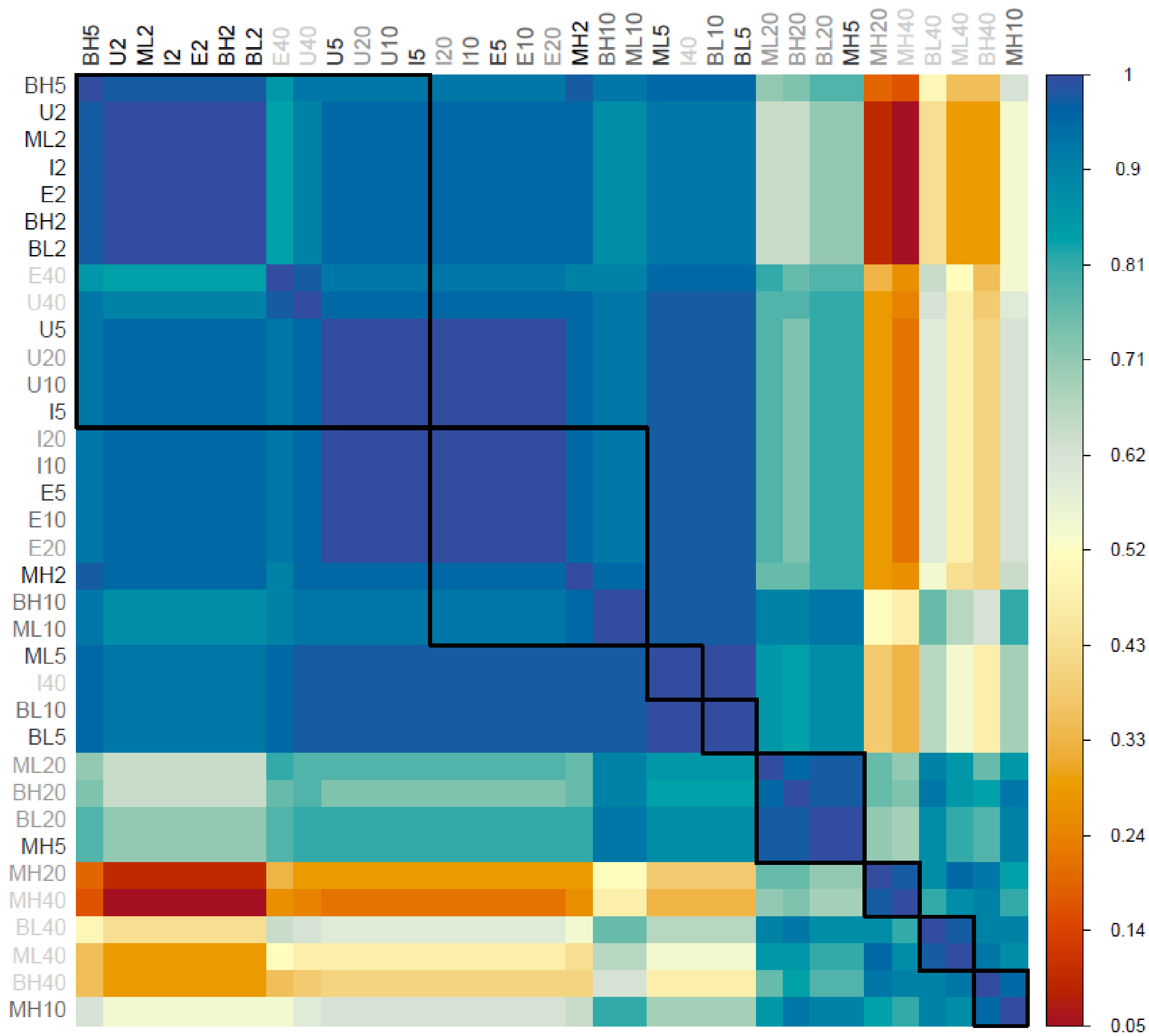

Fig S23. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Arctic Cordillera ecozone.

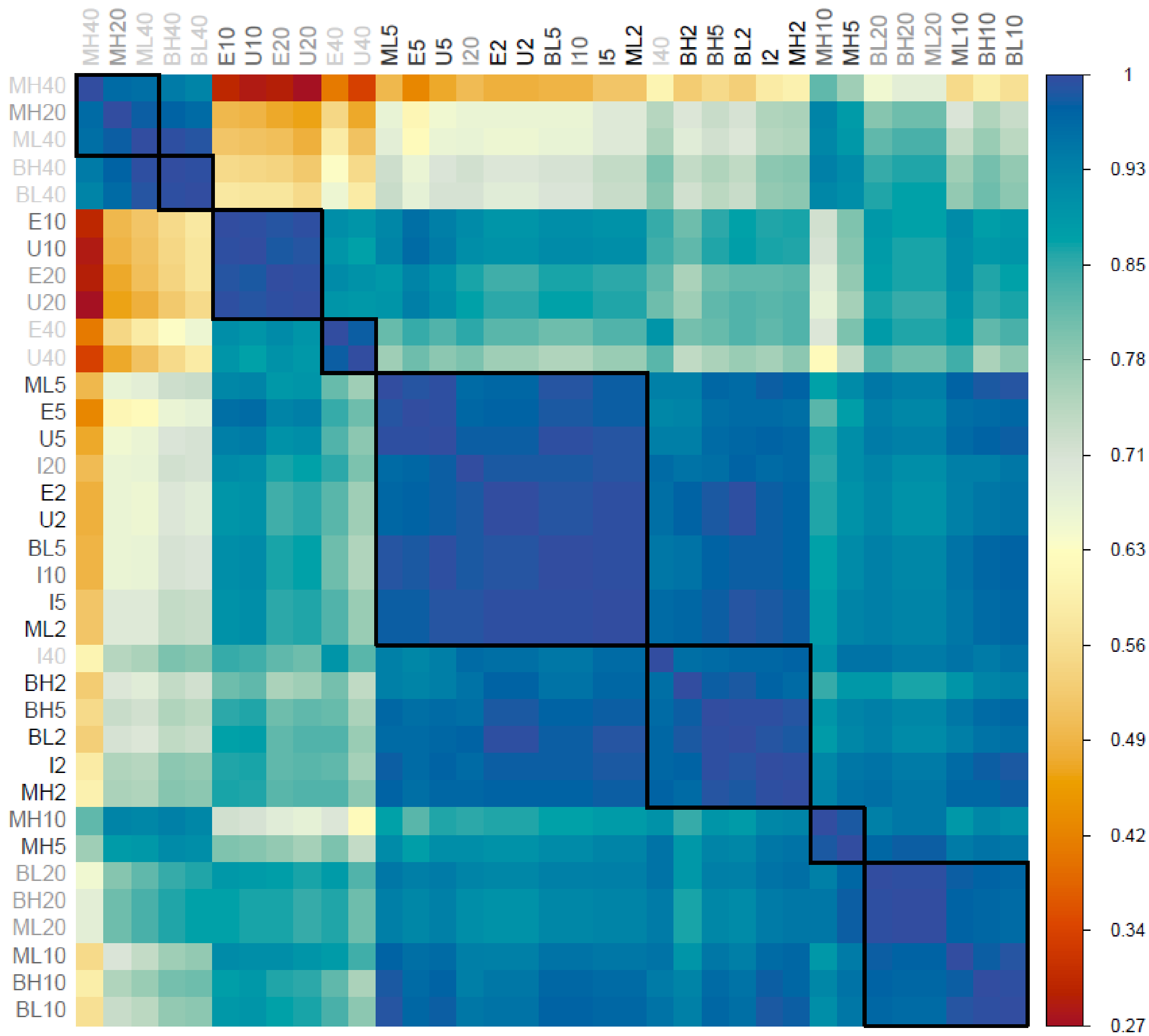

Fig S24. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Taiga Cordillera ecozone.

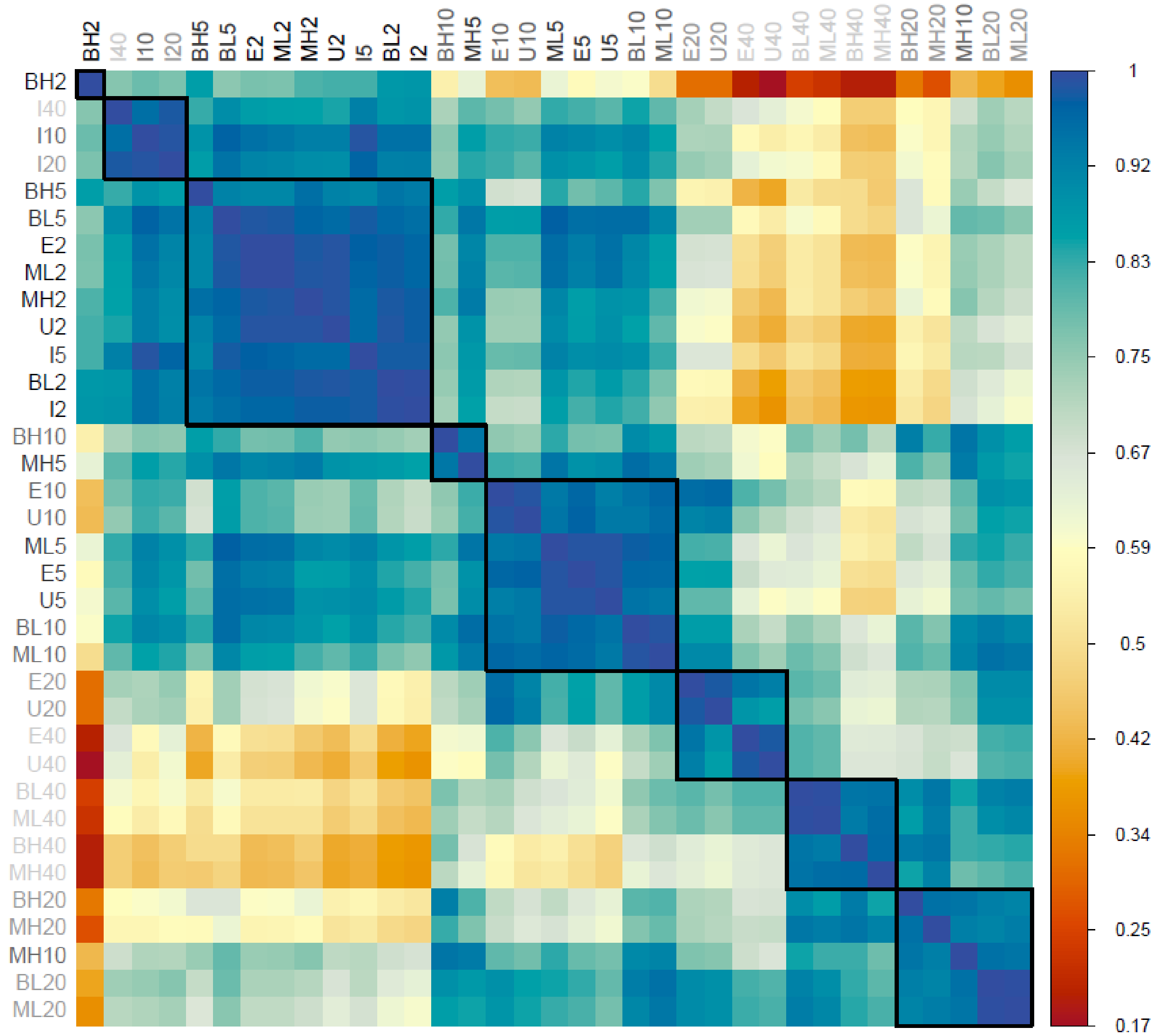

Fig S25. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Boreal Plains ecozone.

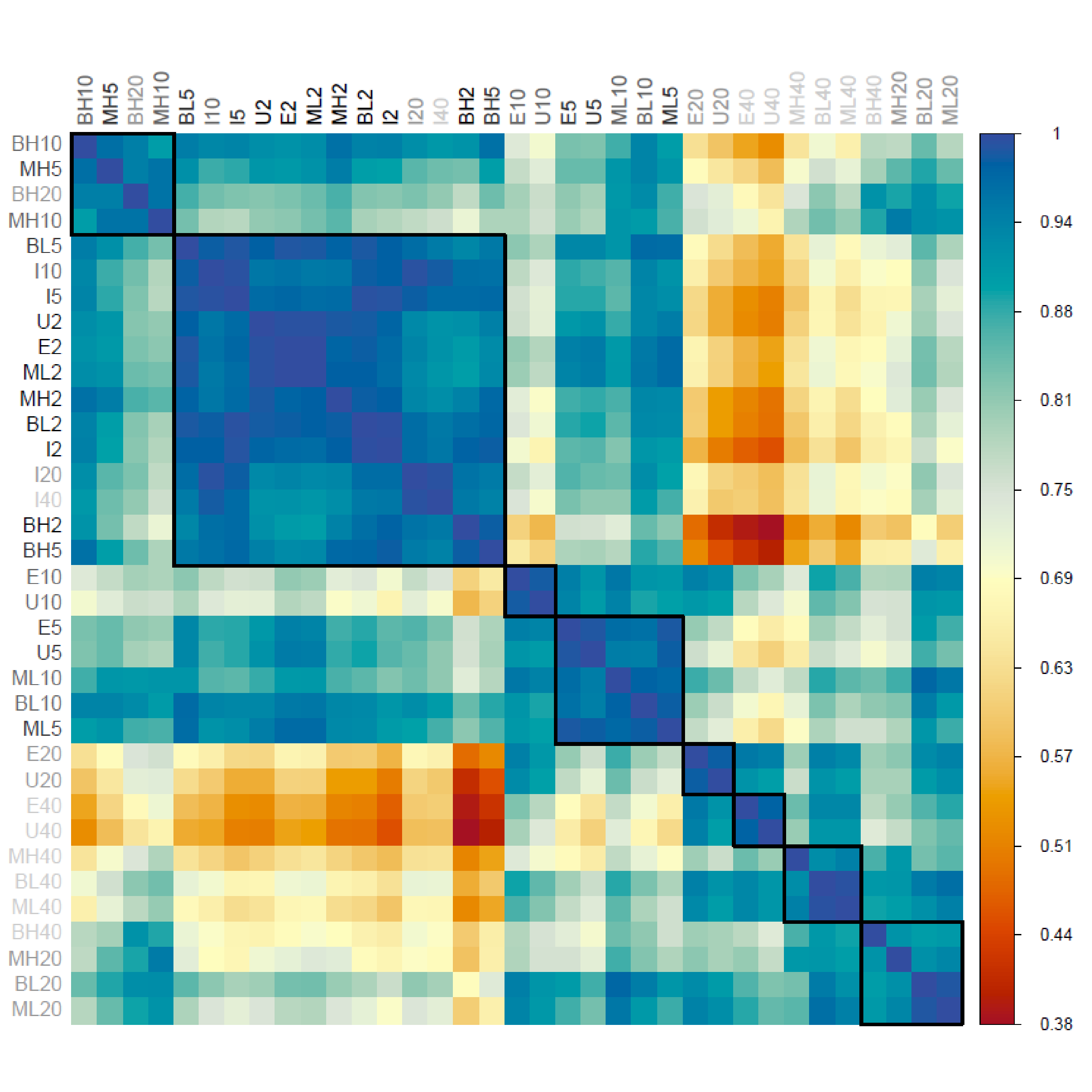

Fig S26. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Taiga Plains ecozone.

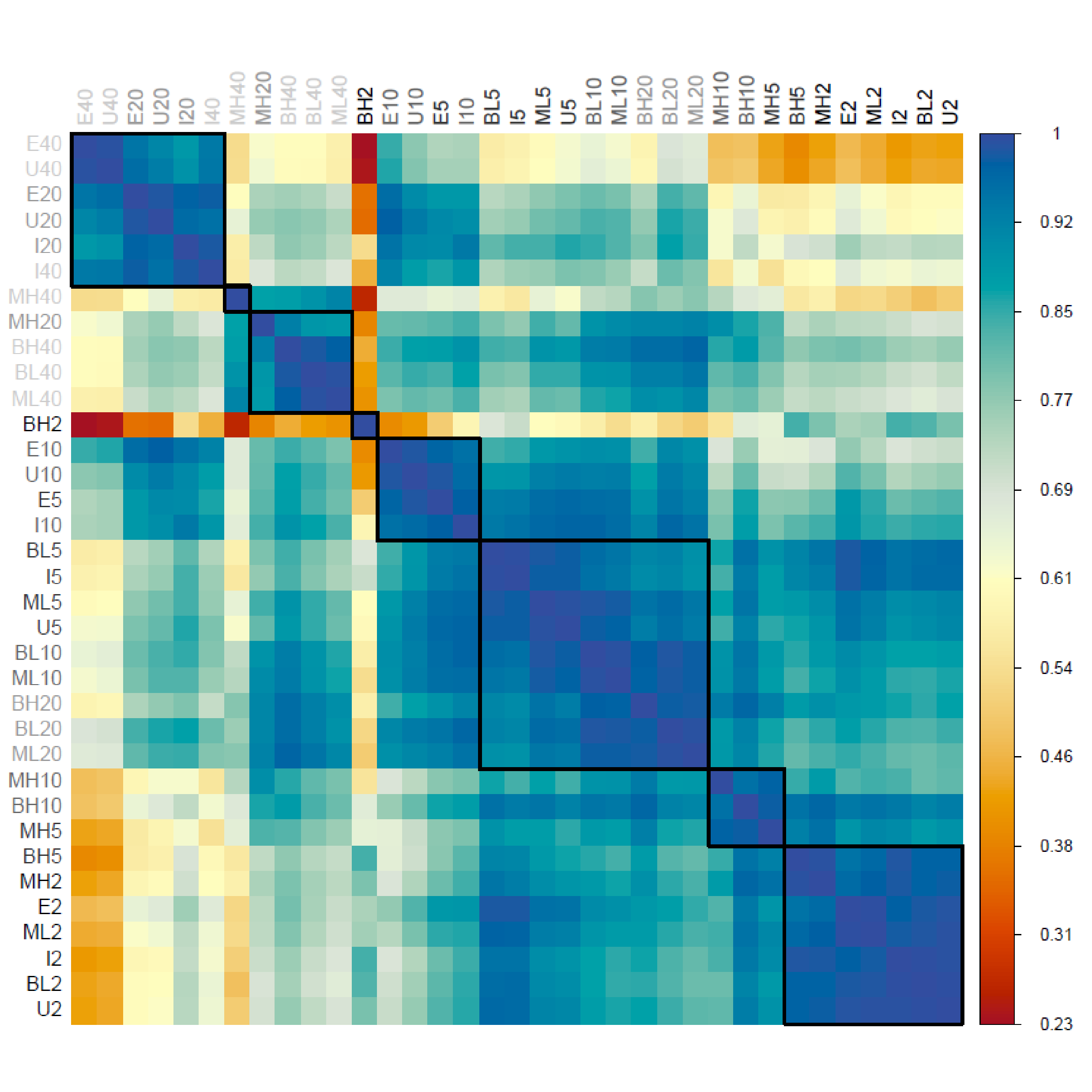

Fig S27. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Southern Arctic ecozone.

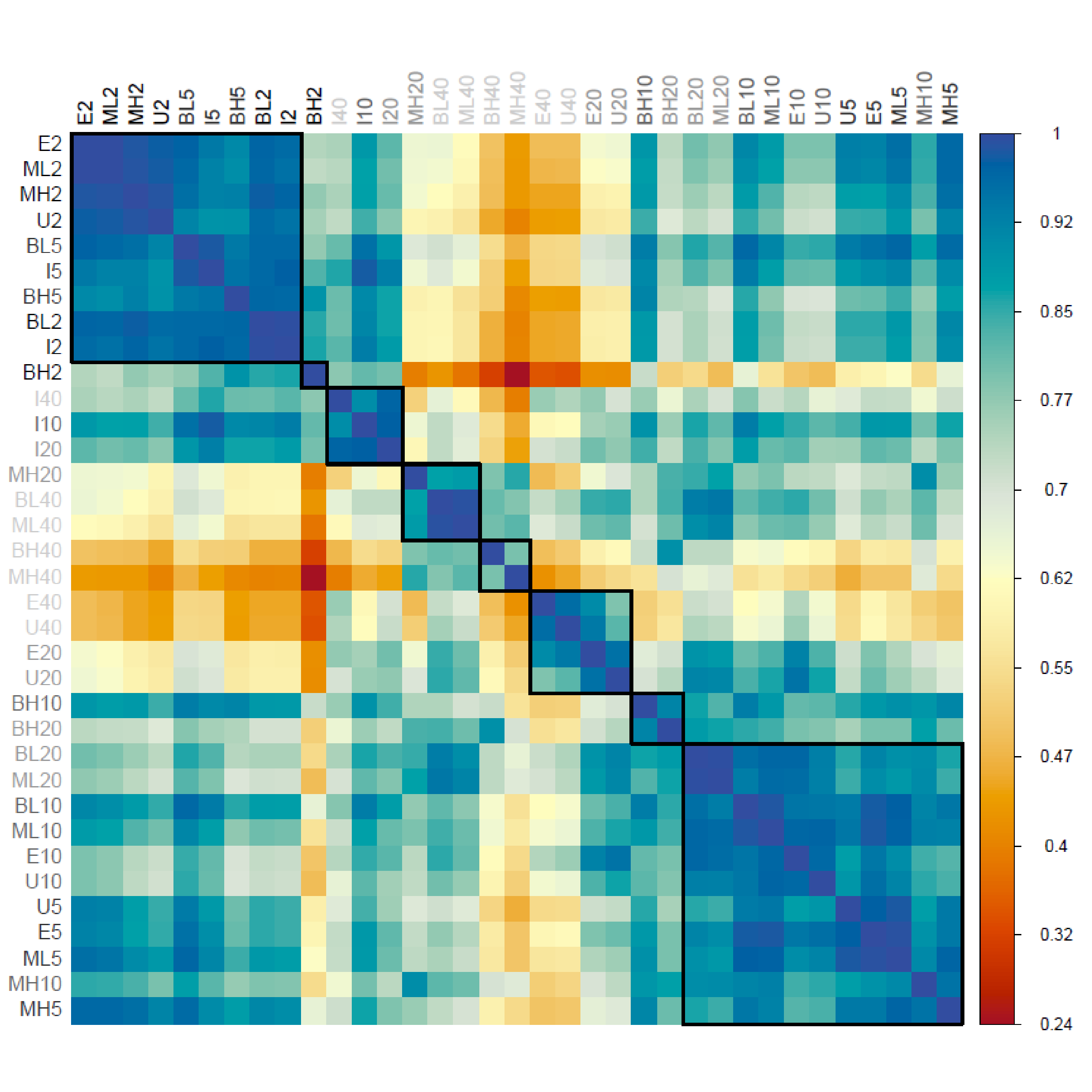

Fig S28. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Boreal Shield ecozone.

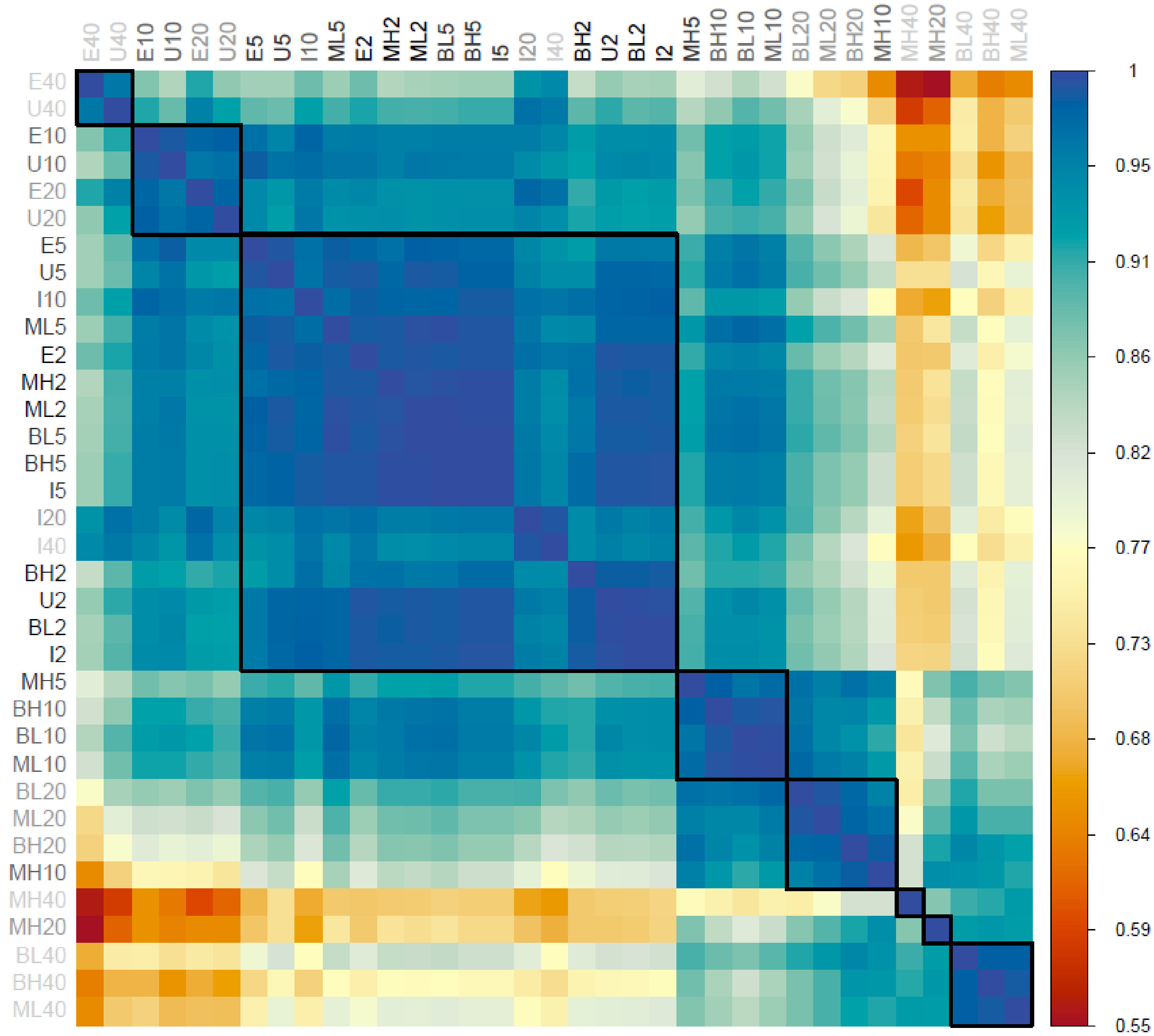

Fig S29. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Taiga Shield ecozone.

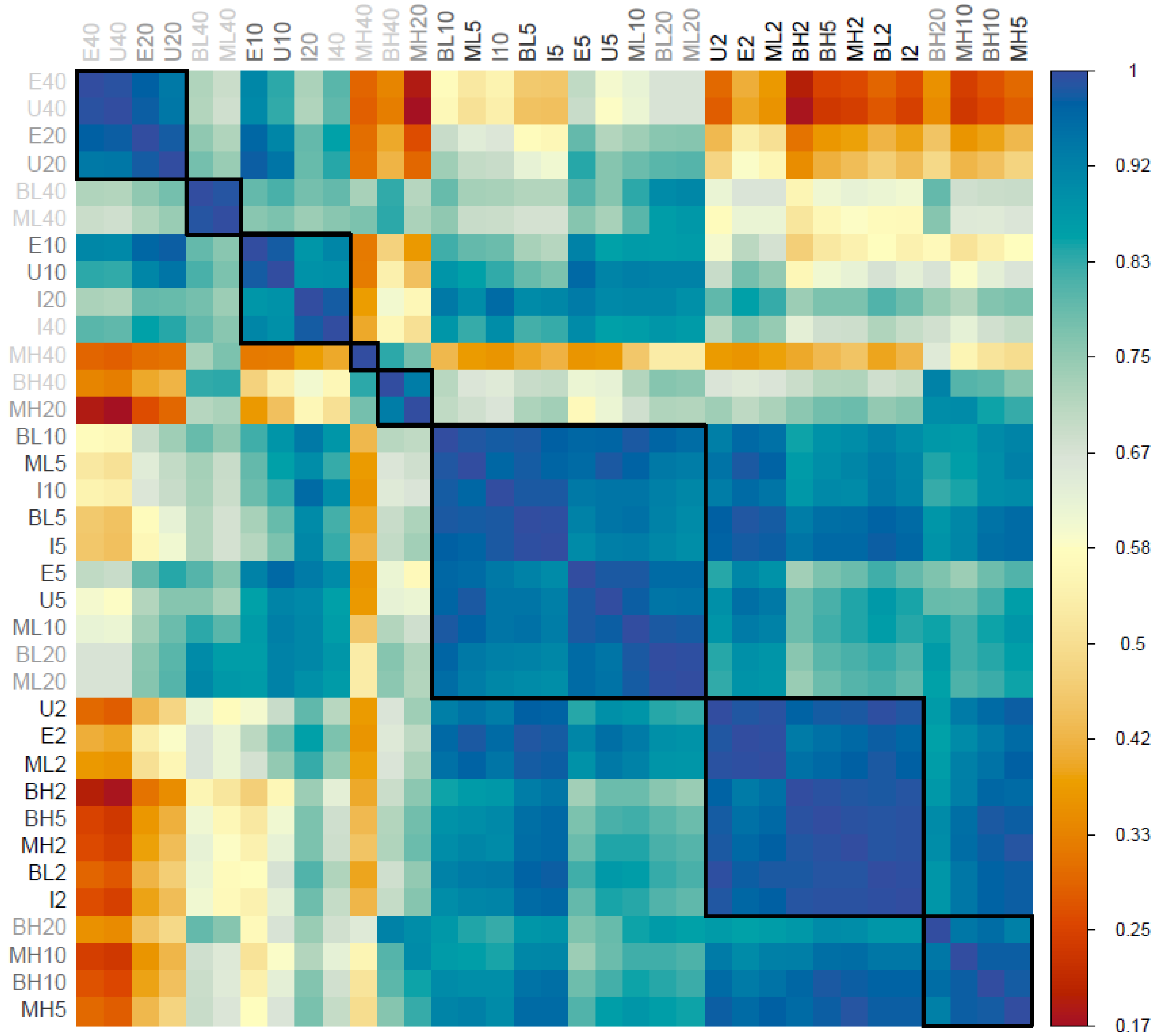

Fig S30. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Hudson Plains ecozone.

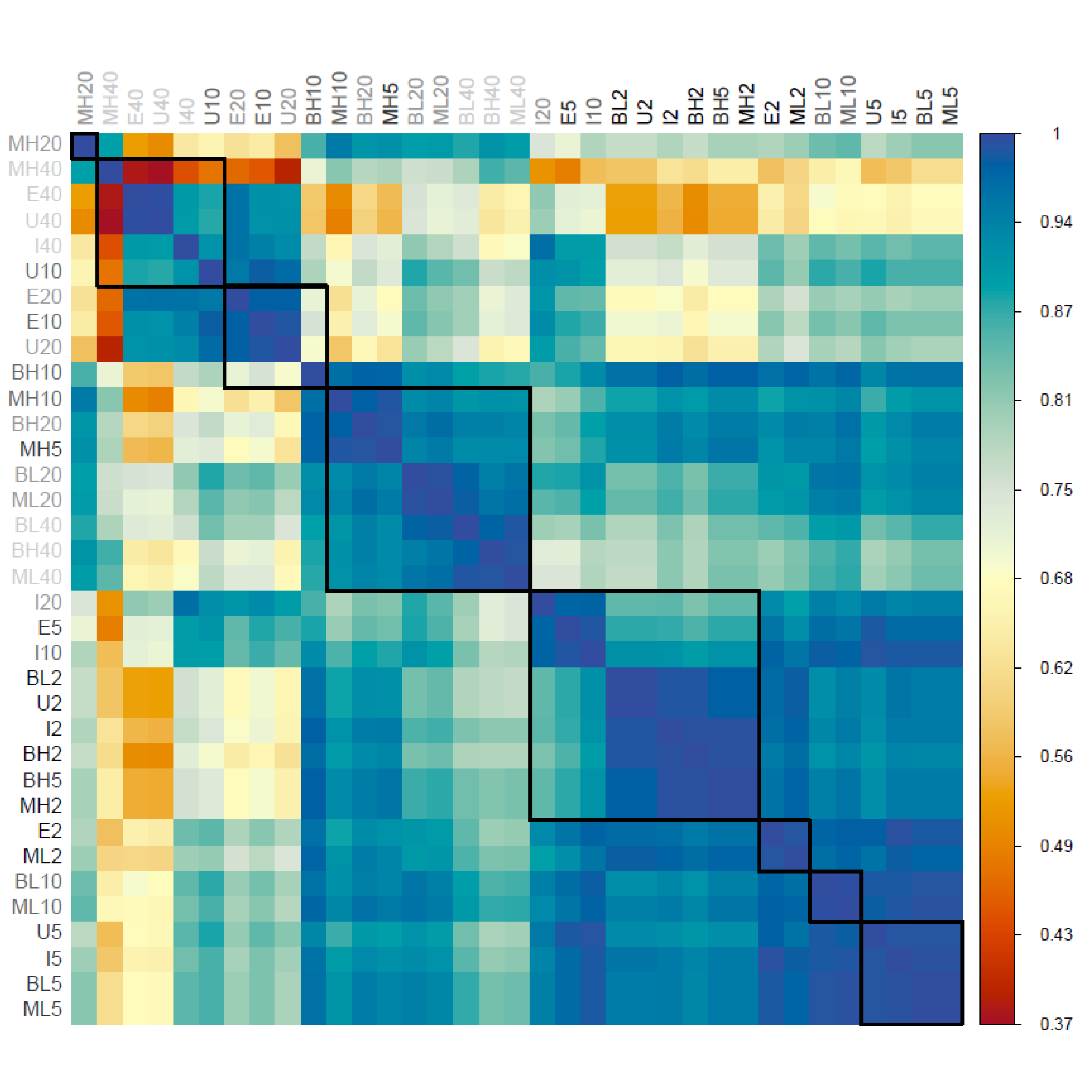

Fig S31. Spearman rank correlations among ratio metric variants (Table 2) for protected areas in the Northern Arctic ecozone.

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