Ecography

ECOG-04716
Huang, J.-L., Andrello, M., Martensen, A. C., Saura, S., Liu, D.-F., He, J.-H. and Fortin, M.-J. 2019. Importance of spatio-temporal connectivity to maintain species experiencing range shifts. – Ecography
doi: 10.1111/ecog.04716

Supplementary material

Appendix 1

Methods

Connectivity metrics

We used the PC family of metrics in our study. PC is the probability that two individuals randomly placed within a landscape fall into habitat patches that are reachable for each other across the habitat network (Saura and Pascual-Hortal 2007). Patch i and j may either be directly connected if they are close enough, or may be indirectly connected through consecutive spatial paths if they are distant, hence it accounts for the stepping-stone effect. The formula is given by:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}{A_l^2}$$

where a_i and a_j are the patch attributes of node i and j (in our case, node attributes were habitat quality, but it can also be patch size, or patch size weighted by habitat quality), respectively; p_{ij}^* is the maximum product probability of all possibly paths (spatial paths for the purely spatial case and spatio-temporal paths for the spatio-temporal case) between i and j; A_l is the area of the study site.

EC is an extended metric of PC. EC is defined as the habitat resources of a single patch (a single Stable patch for the spatio-temporal case) that can provide the same value of probability of connectivity as the actual habitat pattern in a landscape (Saura, et al. 2011). It is independent of the study area A_l, hence it can avoid obtaining very little PC values when habitat area is small compared to the study area (Mailec 2008). Mathematically, EC is the square root of the numerator of PC, which is formulated as:

$$EC = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}.$$

PC can be decomposed into three distinct fractions, in which each indicates a different contribution source to the overall connectivity (Saura, et al. 2014). PC_{intra}^{st} and PC_{intra} correspond to the intra-node connectivity provided by "Stable" patches for the spatio-temporal case and by all patches for the spatial-only case, respectively; PC_{direct}^{st} and PC_{direct} correspond to the inter-node connectivity provided by direct spatio-temporal paths for the spatio-temporal case and by direct spatial paths for the spatial-only case, respectively; PC_{step}^{st} and PC_{step} correspond to the inter-node connectivity provided by indirect spatio-temporal paths (i.e., using stepping-stones) for the spatio-temporal case and by indirect spatial paths for the spatial-only case, respectively. Their formulas are as follows:

$$PC_{intra} = \frac{\sum_{i=1}^{n} a_i^2}{A_l^2},$$

$$PC_{direct} = \frac{\sum_{i=1}^{n}\sum_{j=1,i\neq j}^{n} a_i a_j p_{ij}}{A_l^2},$$

$$PC_{step} = \frac{\sum_{i=1}^{n}\sum_{j=1,i\neq j}^{n} a_i a_j (p_{ij}^* - p_{ij})}{A_l^2},$$

$$P_{ij} = e^{-kd_{ij}},$$

where P_{ij} denotes the dispersal probability from patch i to j; d_{ij} is the distance between i and j, which can either be Euclidean or effective distance when landscape resistance is taken into account; k is a species-specific constant to denote the species dispersal ability.

Supporting Graphs

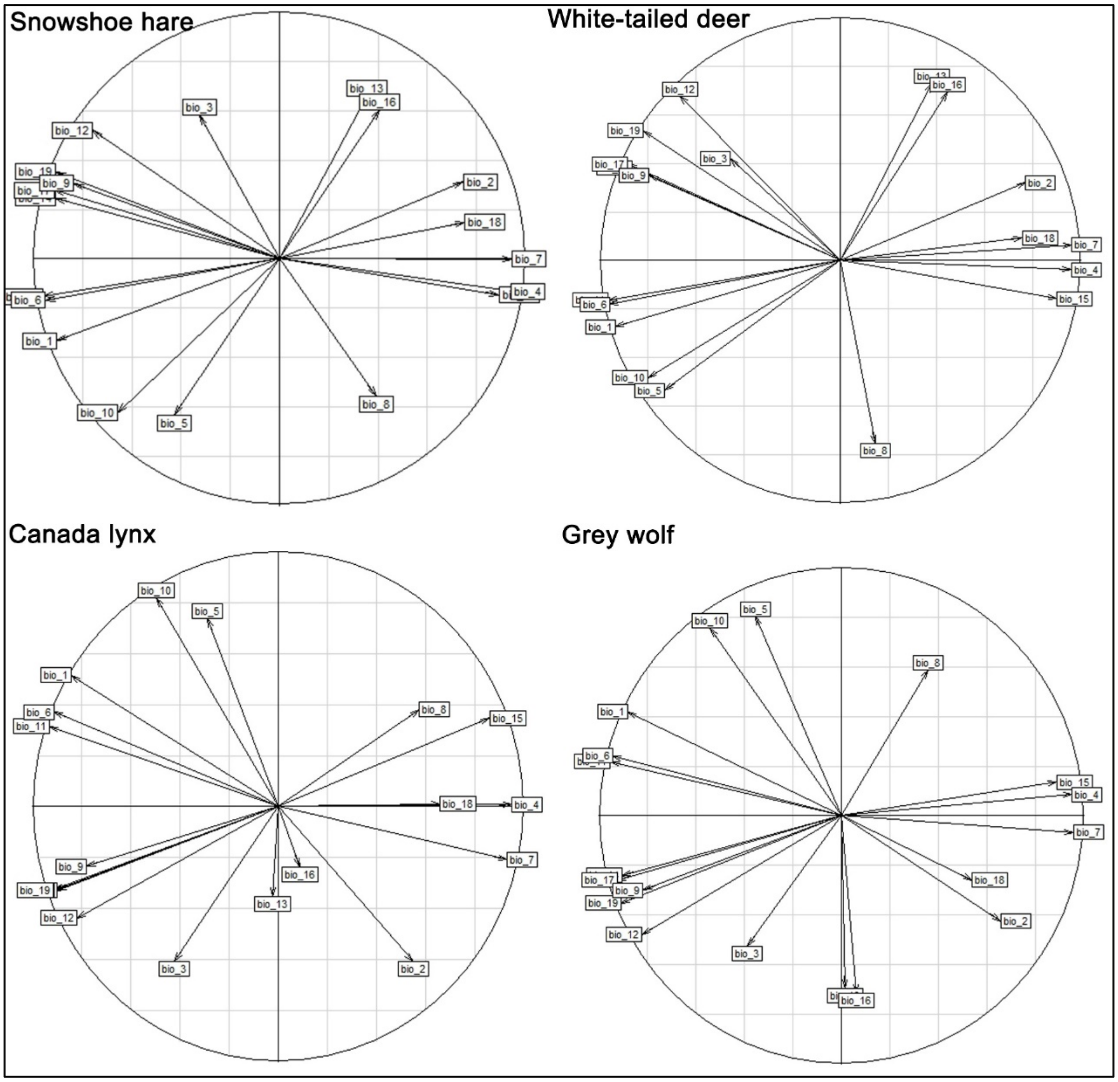

Figure A1. Correlation circles of the bioclimatic variables as a function of the two PCA axes for the actual focal species. Two variables pointing in orthogonal directions are independent, while two variables pointing in the same or opposite directions are highly dependent (positively or negatively, respectively). Additionally, the longer the arrow, the more important the variable. Based on these information and biological knowledge for the focal species, Bio7, 10 and 19 were selected for snowshoe hare (Spearman correlations amongst selected variables: -0.61 ~ 0.48), Bio7, 10, 12 and 17 for white-tailed deer (Spearman correlations range: -0.14 ~ 0.72), Bio10, 11 and 19 for Canada lynx (Spearman correlations range: 0.24 ~ 0.55), and Bio7, 10 and 12 for grey wolf (Spearman correlations range: -0.70 ~ 0.17).

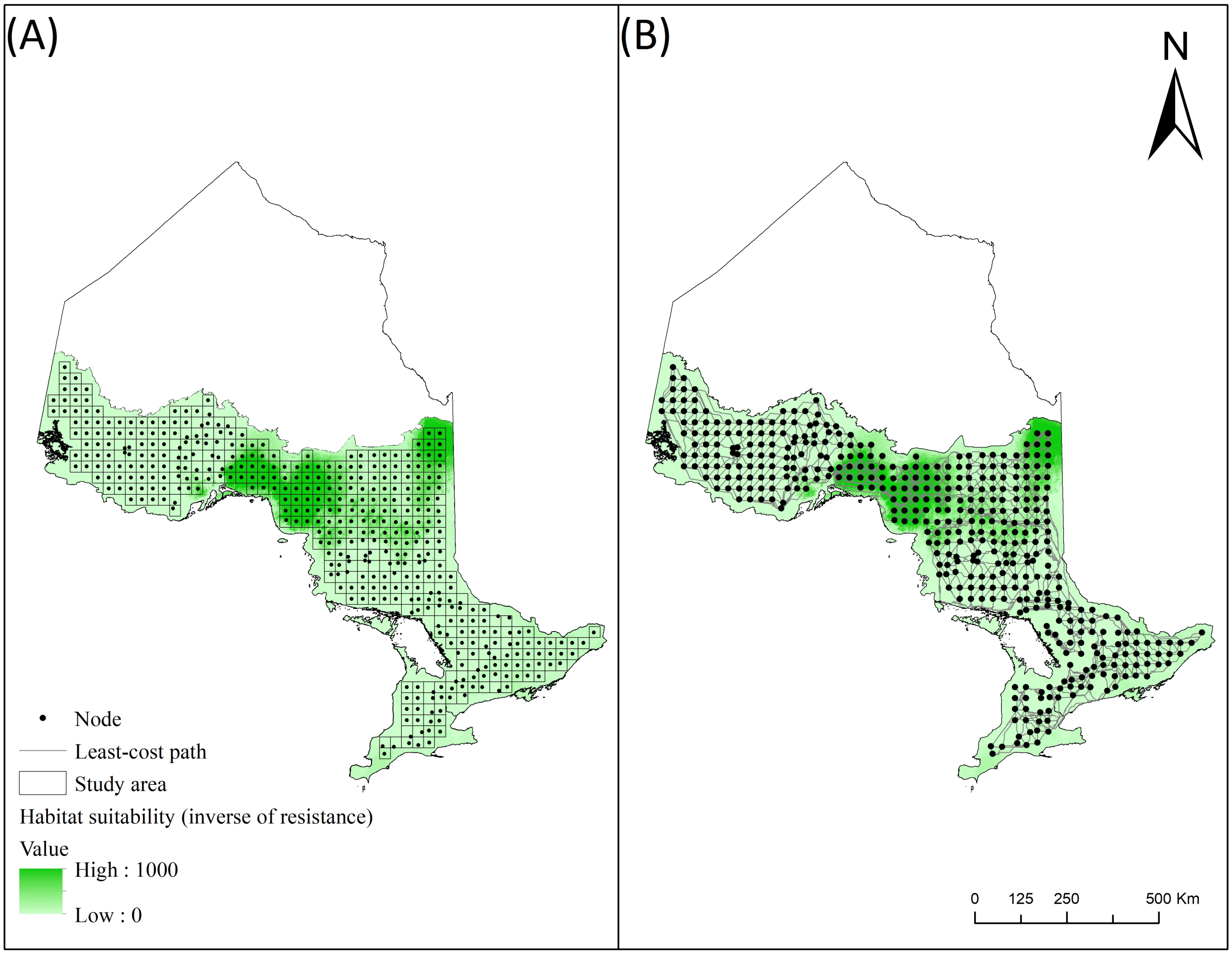

Figure A2. An example (Canada lynx under RCP 6.0) to demonstrate the model parameterization part in the main text. (A): Dividing the study area into 428 equal-size 40 × 40 km blocks, and locating the block centroid in a habitat-suitability-weighted fashion, to account for the uneven distribution within the block. (B): The least-cost path connecting pairs of nodes, derived from the resistance surface (the inverse of habitat suitability).

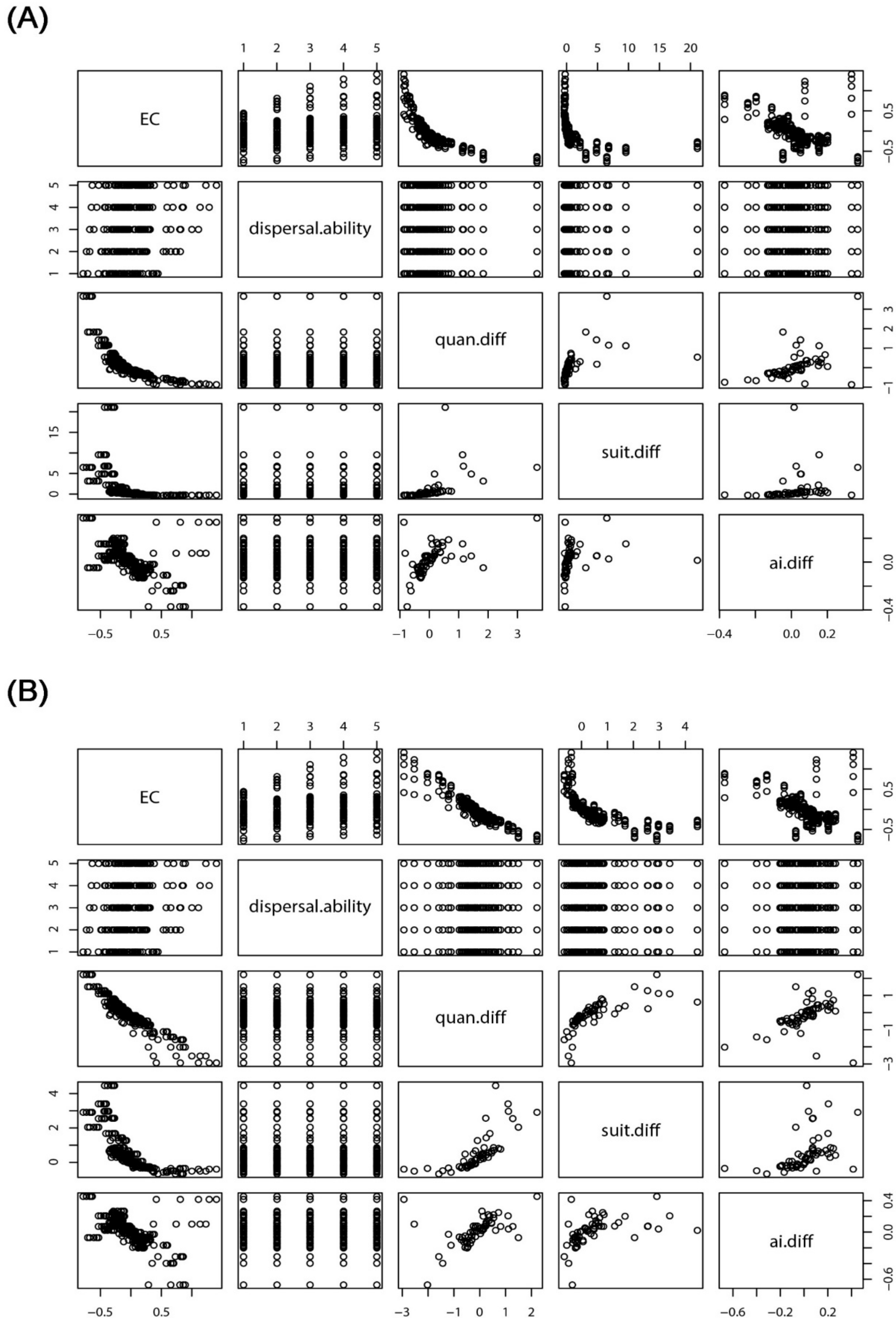

Figure A3. The relationships between explanatory variables and response variable (A) before and (B) after log-transformation. Variables of 'quan.diff', 'suit.diff' and 'ai.diff' denote difference proportions in habitat quantity, habitat suitability and habitat configuration (aggregation index), respectively.

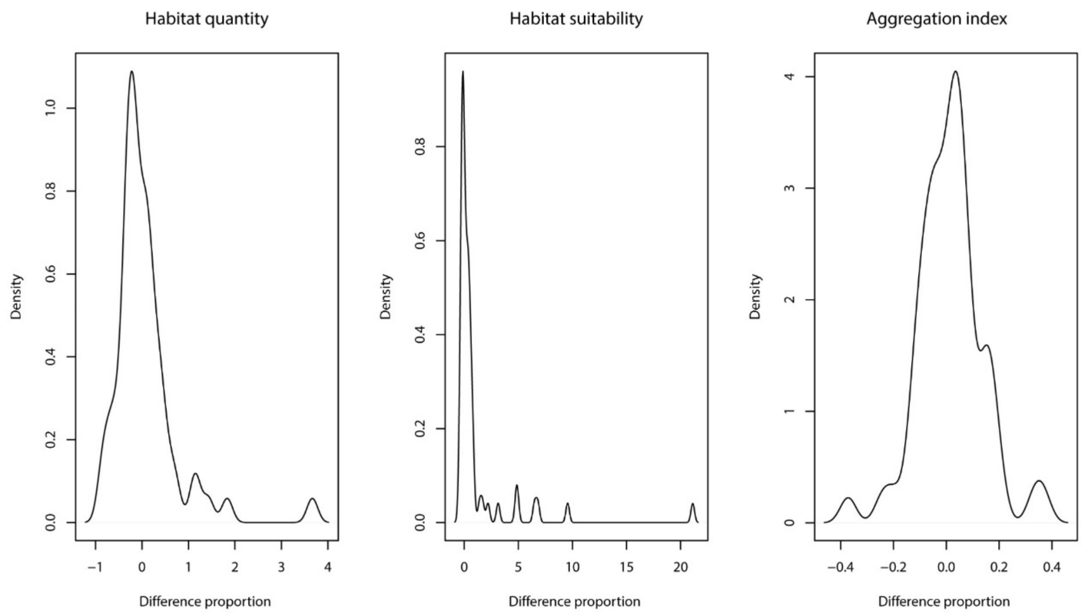

Figure A4. Density distributions of difference proportions of habitat quantity, habitat suitability and aggregation index in the virtual species distributions.

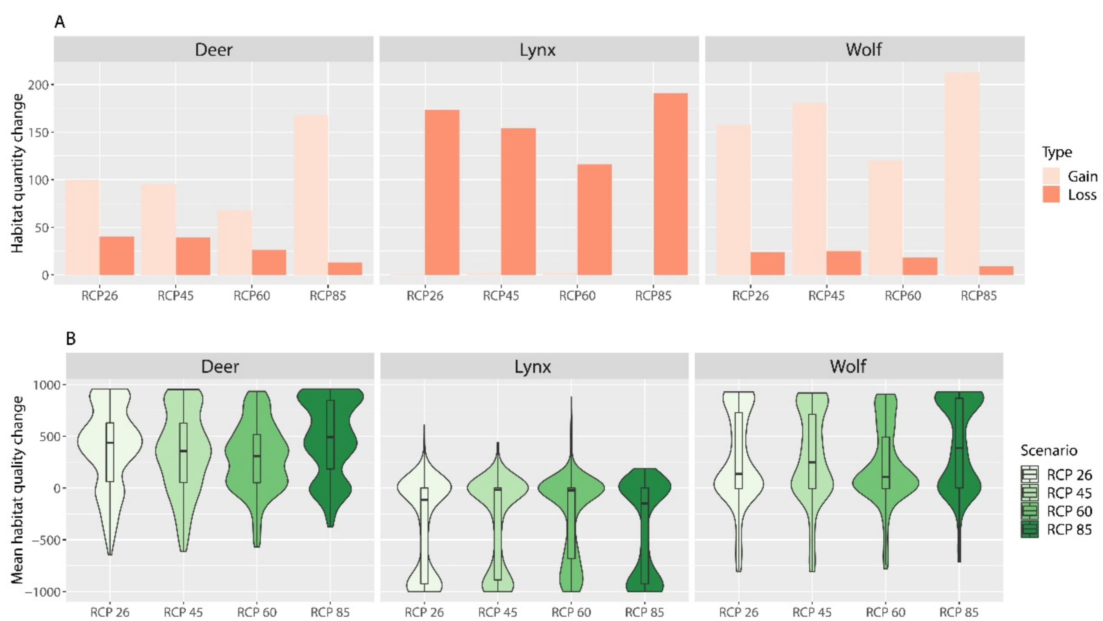

Figure A5. (A) The habitat quantity changes (number of blocks) for each species under future scenarios, where numbers of gained habitat are represented by light orange bars and lost habitat by orange bars. (B) The distribution of changes in mean habitat suitability across the 428 blocks for each species under future scenarios. Positive values indicate that future habitat suitability, on average, is predicted to be higher than the current one.

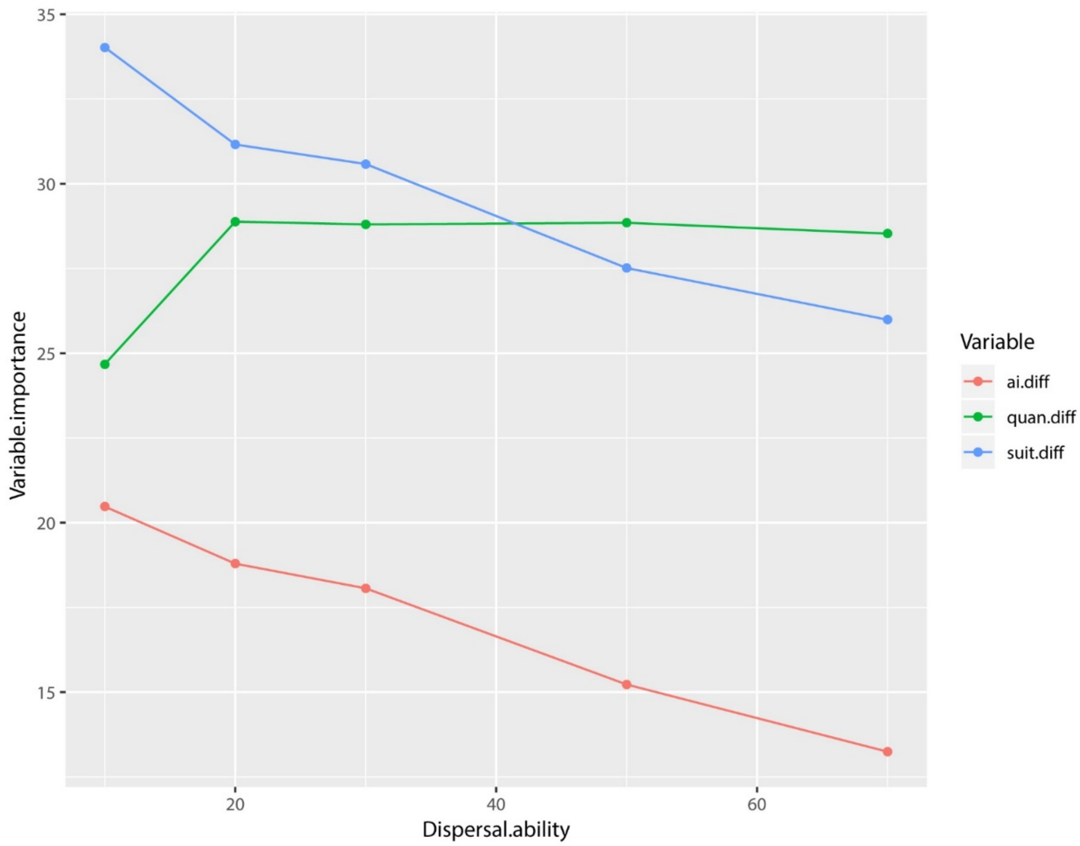

Figure A6. Variable importance in explaining the importance of spatio-temporal connectivity relative to spatial-only connectivity based on random forests algorithm. The importance measure is based on mean decrease in accuracy. Higher values indicate higher variable importance. Variables of 'ai.diff', 'quan.diff' and'suit.diff' denote difference proportions in habitat configuration (aggregation index), habitat quantity and habitat suitability, respectively.

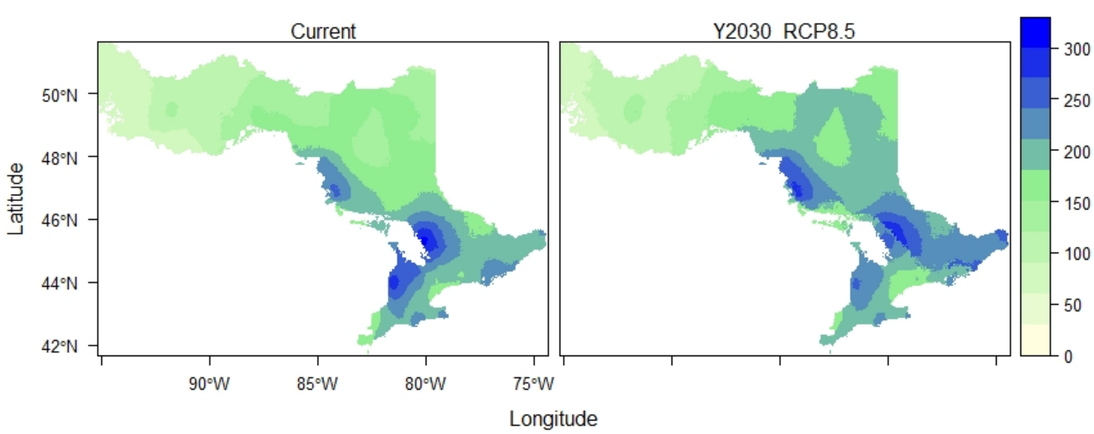

Figure A7. The precipitation of the coldest quarter (Bio_19) under current and future (Yr 2030, RCP 8.5) scenarios.

References

Mailec, N. 2008. Patch connectivity and genetic diversity conservation in the federally endangered and narrowly endemic plant species Astragalus albens (Fabaceae). - Biol. Conserv. 141: 938-955.
Saura, S. and Pascual-Hortal, L. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. - Landscape Urban Plan 83: 91-103.
Saura, S., et al. 2011. Network analysis to assess landscape connectivity trends: Application to European forests (1990-2000). - Ecol Indic 11: 407-416.
Saura, S., et al. 2014. Stepping stones are crucial for species' long-distance dispersal and range expansion through habitat networks. - J. Appl. Ecol. 51: 171-182.