Supporting Information

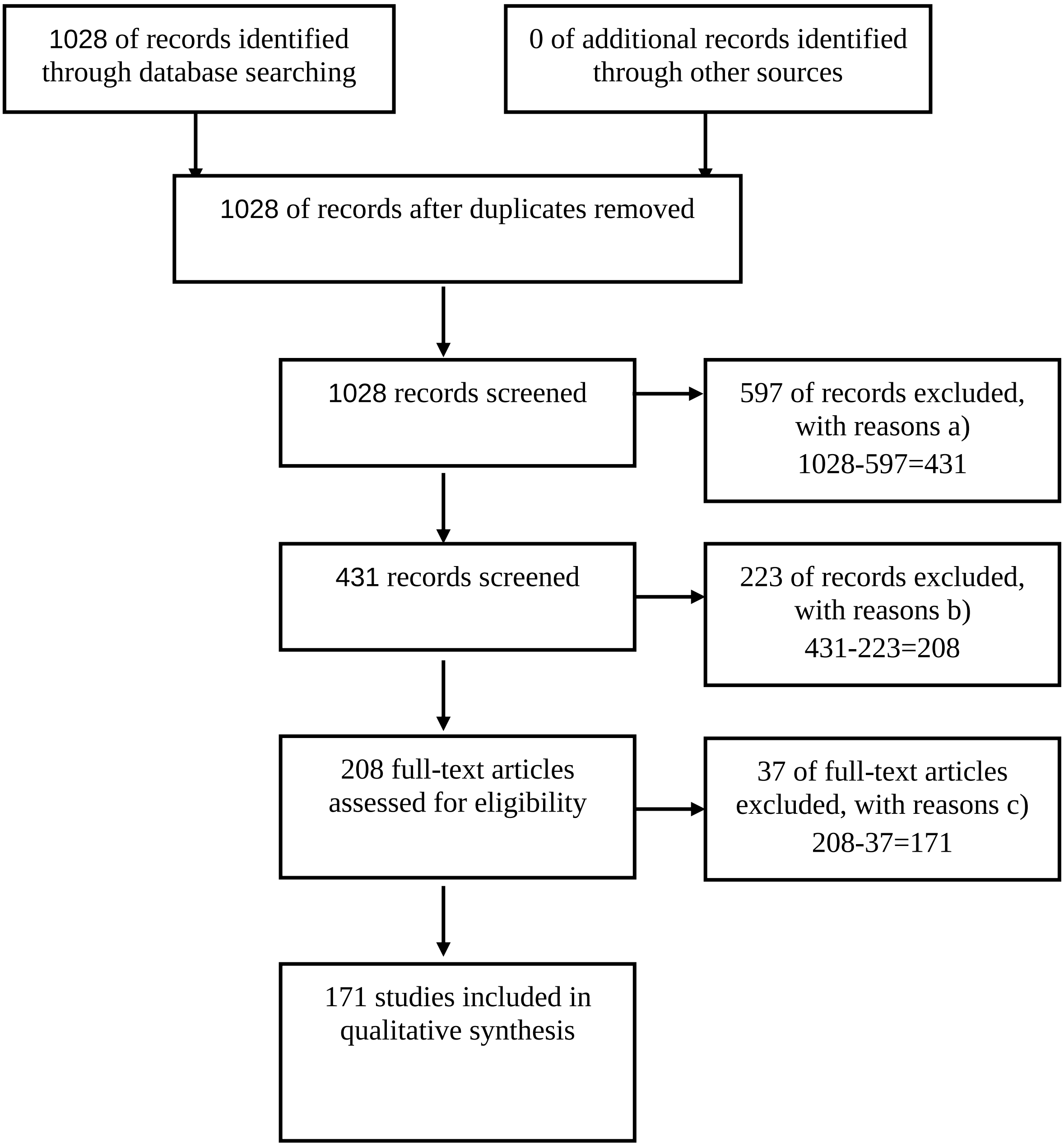
Rapid evaluation of habitat connectivity change to safeguard multispecies persistence in human-transformed landscapes

Jacqueline Oehri[1,2*], Sylvia L.R. Wood[2], Eluna Touratier[1], Brian Leung[1], Andrew Gonzalez[1,2]

[1]Department of Biology, McGill University, 1205 avenue Docteur Penfield, Montreal, QC, Canada H3A 1B1
[2]Habitat, 5818 Saint-Laurent Boulevard, Montreal, QC, Canada H2T1T3

*Correspondence: jacqueline.oehri@gmail.com

Appendix S1



Supporting Figure 1. PRISMA flow diagram (Liberati et al., 2009) describing the selection procedure in our literature review. Using our search string (cf. Methods), we searched the Scopus and Web of Science databases on January 24th, 2022, and found 1028 journal articles published since January 1, 2000. Reasons to exclude studies: **a)** articles that did not mention either connectivity or monitoring in their title, **b)** articles that i) were not concerned with habitat connectivity, ii) were not primary research articles, iii) did not use any indicator of connectivity, and iv) were focused on a single species only, whereby we kept articles that used a single species as umbrella species. **c)** articles that did not align with our criteria in a) or b).

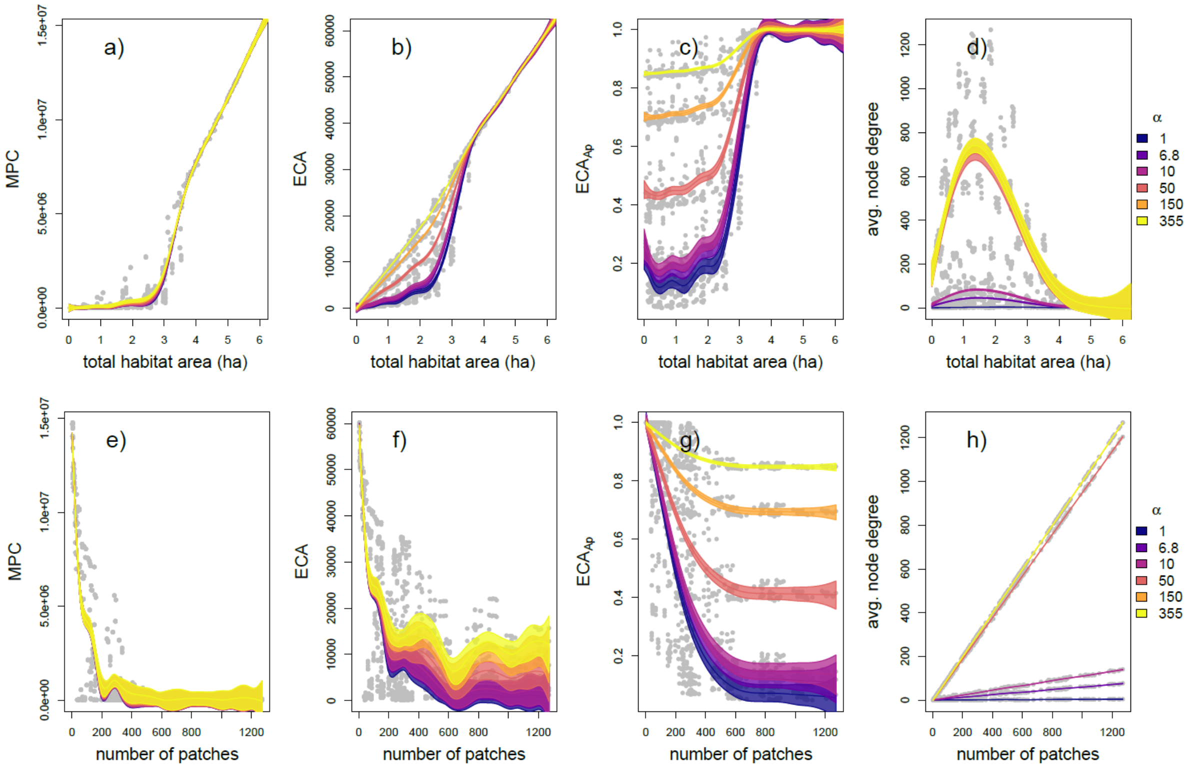
Appendix S2

Supporting Table 1. Criteria for the selection of key-connectivity indicators[1].

Nr	**Abbreviation**	**feasibility (commonness, ease of computation)**	**relevance (alignment with target)**	**scalability**	**sensitivity**	**scale, interpretation**
1	**MPC**	high, >3 case studies, binary habitat distribution maps	species persistence	yes	yes	landscape level species persistence
2	**ECA**	high, >3 case studies, binary habitat distribution maps	area-based conservation	yes	yes	landscape level amount of connected area
3	**ECA_{Ap}**	low, 0 case studies, binary habitat distribution maps	area-based conservation	yes	yes	landscape level fraction of habitat that is connected
4	**ECA_{AI}**	high, >3 case studies, binary habitat distribution maps	area-based conservation	yes	yes	landscape level amount of habitat that is connected
5	**BC**	high, >3 case studies, binary habitat distribution maps	spatial prioritization	yes	yes	patch level importance for short and long-range movement
6	**ND**	high, >3 case studies, binary habitat distribution maps	spatial prioritization	yes	yes	patch level importance for short-range movement
7	**invCR**	medium, 1 case study, resistance map	spatial prioritization	yes	yes	pixel level contribution to short- and long-range movement
8	**I_v**	high, >3 case studies, binary habitat distribution maps	spatial prioritization	yes	yes	patch level contribution to landscape level connectivity index I
9	**MPC_i**	high, >3 case studies, binary habitat distribution maps	spatial prioritization	yes	yes	patch level contribution to landscape level metapopulation capacity

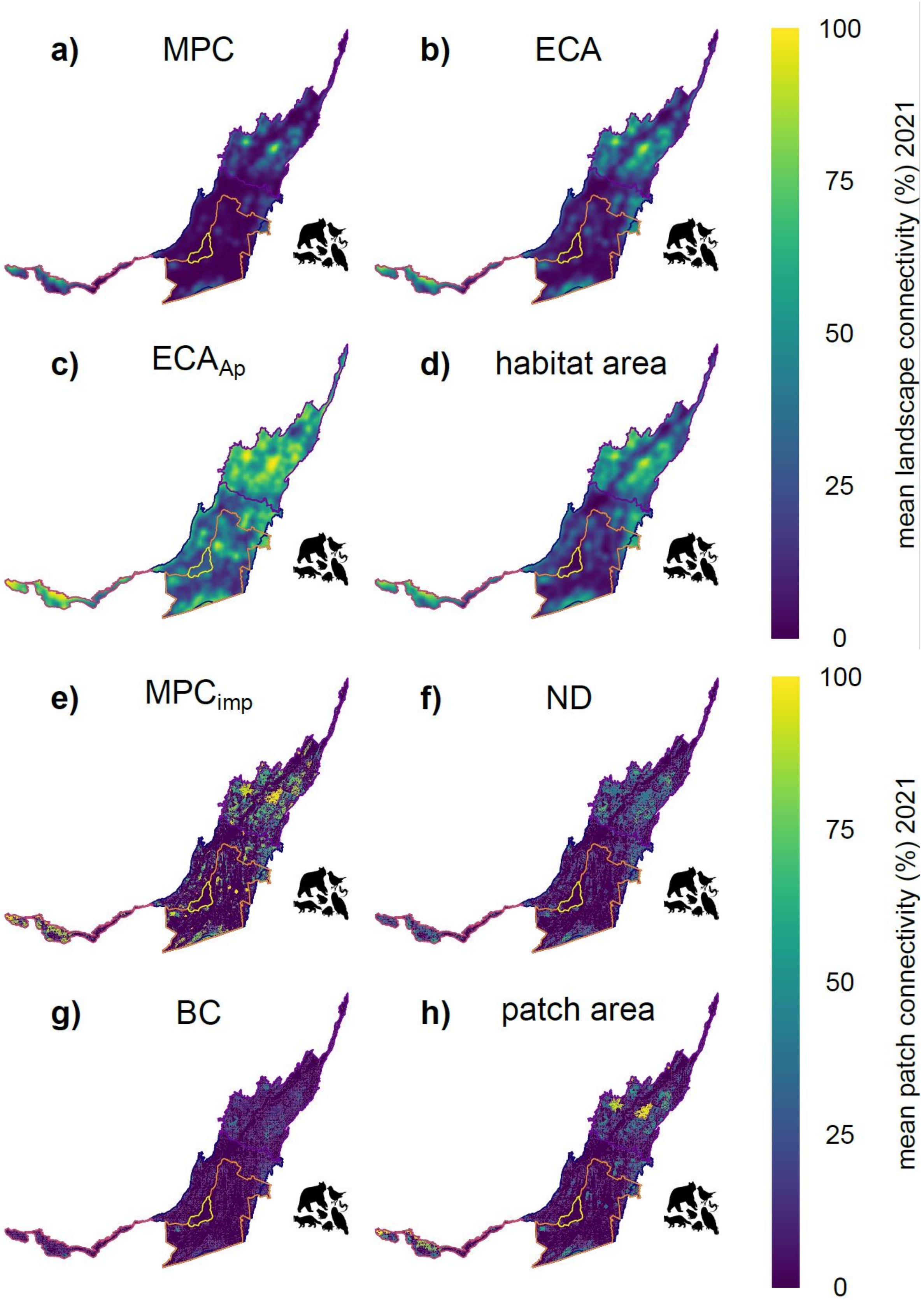
[1] We selected key-connectivity indicators identified in our literature review based on feasibility, relevance, scalability and sensitivity criteria established in the Essential Biodiversity Variable's framework (EBV) (Balvanera et al., 2022; Jetz et al., 2019; Pereira et al., 2013). The list of selected indicators includes graph-based metrics (Minor & Urban, 2008) such as the effectively connected habitat area (Saura, Bastin, Battistella, Mandrici, & Dubois, 2017) (ECA), and the importance of stepping stones (Albert et al. 2017) (betweenness centrality [BC] and node degree [ND]), resistance-distance derived proxies of landscape traversability (Albert et al., 2017; Chubaty, Galpern, & Doctolero, 2020; Shahnaseri et al., 2019) (invCR), and metapopulation-model derived long-term persistence of species (Hanski & Ovaskainen, 2000; Schnell et al., 2013) (MPC). These connectivity indicators also span different and complementary scales of spatial organization (Fletcher et al., 2023). For example, ECA and MPC are typically assessed at the scale of a landscape, BC and ND are typically assessed at the scale of habitat patches, and finally, resistance-based proxies of landscape traversability such as invCR are assessed at the pixel (or plot) level (Fletcher et al., 2023). We assessed the sensitivity of selected indicators to changes in habitat area and fragmentation by means of simulated and real-world landscapes (see Figure 5 and Appendix S3).

Appendix S3



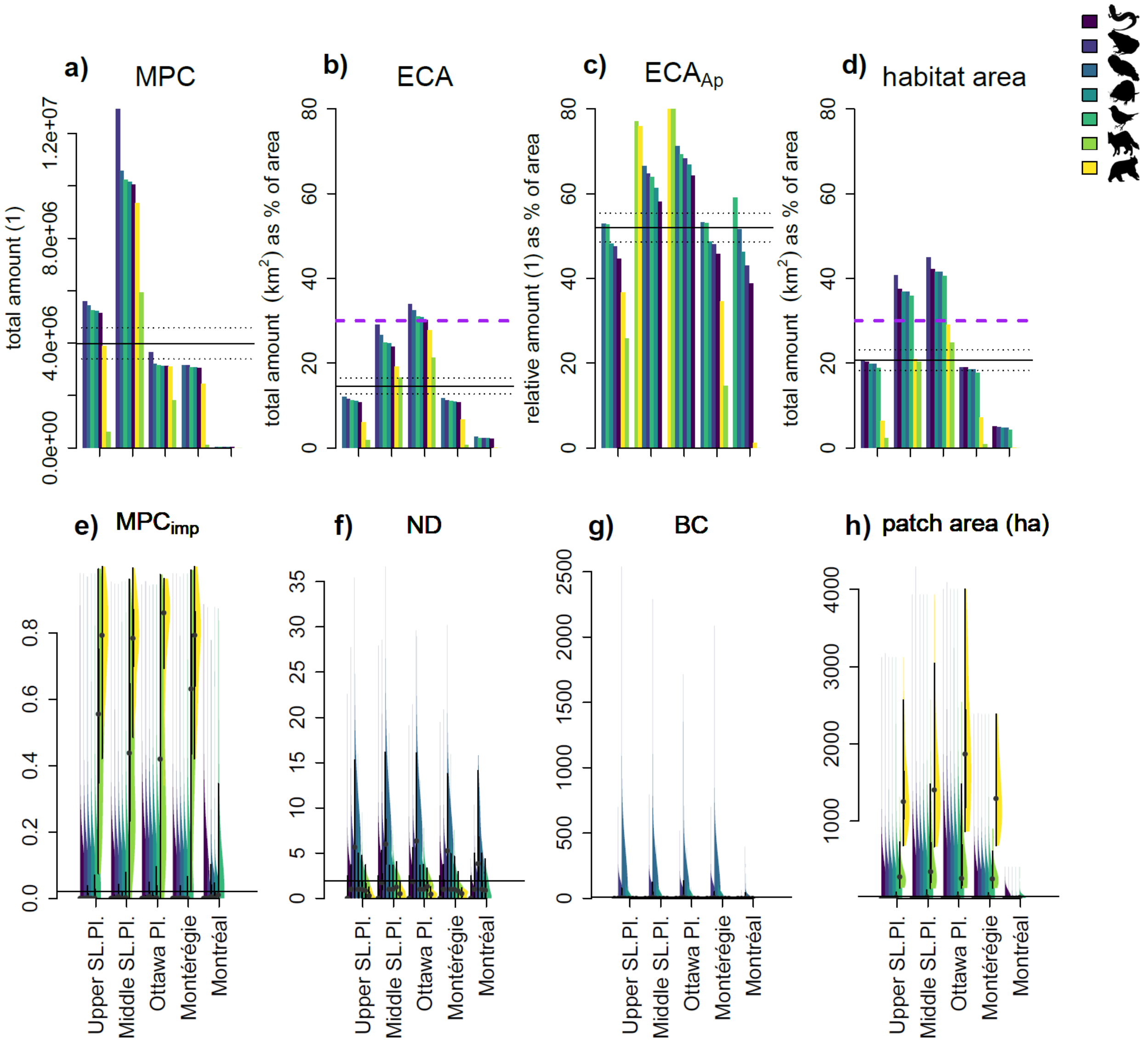
Supporting Figure 2. Change of multiple connectivity dimensions with total habitat area (a-d) and habitat fragmentation (approximated by the number of habitat patches, e-h) in simulated landscapes (Saura & Martínez-Millán, 2000). Landscape-level connectivity values (Table 1) were calculated using the RE-Connect R-tool and a library of 270 simulated landscapes varying in habitat area and fragmentation for different dispersal capacities (Methods). Compared with landscape size (250 x 250 cells), a gap crossing distance of 6.8 corresponds most closely to the maximum of the gap crossing distance among our species (236 m) in the 75 km^2 moving windows (~1/36 of the landscape side length, cf. Methods). Relationships among variables were estimated and predicted (fitted values ± standard error) using the smooth spline function in the npreg R-package (Helwig, 2021). **a & e)** MPC: metapopulation capacity, **b & f)** ECA: equivalent connected area index, **c & g)** ECA$_{Ap}$: fraction of habitat that is connected, **d & h)** average node degree of habitat patches in the landscape.

Appendix S4



Supporting Figure 3. State of multispecies connectivity at landscape-level (a-d) and patch-level (e-h) across the St-Lawrence Lowlands in 2021. Using RE-Connect, we mapped the spatial distribution of multiple connectivity dimensions (Table 1), normalized and averaged across seven ecoprofile species representing forest connectivity needs (cf. Methods and Table 2). **a)** MPC: metapopulation capacity, **b)** ECA: equivalent connected area index, based on the probability of connectivity index (PC), **c)** ECA_{Ap}: fraction of habitat that is connected (ECA divided by the total amount of habitat area), **d)** habitat area: area of habitat, **e)** MPC_{imp}: metapopulation capacity patch importance, i.e. the contribution of a habitat patch to landscape-level metapopulation capacity, **f)** ND: node degree of a focal patch, i.e. the number of other habitat patches connected to the focal patch, **g)** BC: betweenness centrality of a focal patch, i.e. the number of shortest paths between all other pairs of habitat patches in the landscape that go through the focal patch, **h)** patch area: area of the focal patch.

Appendix S5



Supporting Figure 4. Status (2021) of multispecies connectivity at landscape-level (a-d) and patch-level (e-h) for 7 species in 5 different regions in the St-Lawrence Lowlands. **a)** MPC: metapopulation capacity, **b)** ECA: equivalent connected area index, based on the probability of connectivity index (PC), **c)** ECA$_{Ap}$: fraction of habitat that is connected (ECA divided by the total amount of habitat area), **d)** habitat area: species-specific area of habitat in the landscape, **e)** MPC$_{imp}$: metapopulation capacity patch importance, i.e. the contribution of a habitat patch to landscape-level metapopulation capacity, **f)** ND: node degree of a focal patch: the number of other habitat patches connected to the focal patch, **g)** BC: betweenness centrality of a focal patch: the number of shortest paths between all other pairs of habitat patches in the landscape that go through the focal patch, **h)** patch area (ha): habitat patch area in hectares. We multiplied RE-Connect-derived landscape-connectivity values with the area they cover in km^2 and consequently summed the results for each region. We scaled connectivity values by the area of the RE-Connect moving window size (8,700^2 = 75.69 km^2) prior to the summation if necessary, i.e. in the cases of MPC, ECA and habitat area. We divided the results by the total area of each region (in km^2) and multiplied by 100, in order to get relative area estimates in % (y-axis, b-d). For the patch-level connectivity indicators, we extracted the median and interquartile range (violin plots, values per patch on y-axes e-h). Black horizontal bars indicate the mean and s.e. of connectivity values across all regions and species. Purple horizontal bars indicate a 30% (connected-) habitat area target as described in Target 3 of the Post-2020 Global Biodiversity Framework of the Convention on Biological Diversity (CBD, 2021). See Appendix S6 and S7 for more details.

Appendix S6

Supporting Table 2. Total amount (2021) and change in amount (Δ, 2011-2021) of landscape-level forest connectivity for 7 ecoprofile species and 5 regions in the St-Lawrence Lowlands[1].

region	**species**	**MPC** total amount (1) 2021	**ΔMPC** total amount (1) 2011-2021	**ECA** total amount (km^2) 2021	**ΔECA** total amount (km^2) 2011-2021	**ECAf** fraction of area (%) 2021	**ΔECAf** fraction of area (%) 2011-2021	**ECA$_{Ap}$** fraction of area (%) 2021	**ΔECA$_{Ap}$** fraction of area (%) 2011-2021	**habitat area** total amount (km^2) 2021	**Δhabitat area** total amount (km^2) 2011-2021	**habitat area_f** fraction of area (%) 2021	**Δhabitat area_f** fraction of area (%) 2011-2021
Upper SL.Pl.	BLBR	5218326	-1452345	1923	-113	11.11	-0.65	48.16	-6.05	3435	133	19.84	0.77
Upper SL.Pl.	MAAM	615606	-718270	302	-214	1.75	-1.23	25.88	-10.29	388	-249	2.24	-1.44
Upper SL.Pl.	PLCI	5149670	-1483233	1859	-131	10.74	-0.76	44.56	-8.07	3522	209	20.34	1.21
Upper SL.Pl.	RASY	5598822	-1270356	2008	-53	11.60	-0.31	47.59	-6.55	3562	232	20.57	1.34
Upper SL.Pl.	SEAU	5252811	-1442902	1939	-115	11.20	-0.66	52.66	-3.19	3275	17	18.92	0.10
Upper SL.Pl.	STVA	5441259	-1430513	2095	-94	12.10	-0.54	52.93	-5.54	3435	133	19.84	0.77
Upper SL.Pl.	URAM	3885946	-1693446	1042	-256	6.02	-1.48	36.72	-7.54	1113	-230	6.43	-1.33
Middle SL.Pl.	BLBR	10159294	-3678927	2749	-236	24.64	-2.11	61.24	-5.15	4110	33	36.85	0.29

Middle SL.Pl.	MAAM	5934772	877180	1840	252	16.50	2.26	76.95	3.34	2258	214	20.24	1.92
Middle SL.Pl.	PLCI	10042053	-3719929	2664	-253	23.88	-2.27	58.01	-6.63	4181	97	37.48	0.87
Middle SL.Pl.	RASY	12939631	-1990065	3241	115	29.05	1.03	64.62	-2.44	4549	335	40.78	3.00
Middle SL.Pl.	SEAU	10221514	-3665987	2773	-240	24.86	-2.15	63.93	-3.64	4006	-50	35.91	-0.44
Middle SL.Pl.	STVA	10571627	-3623517	2968	-212	26.61	-1.90	66.57	-4.69	4110	33	36.85	0.29
Middle SL.Pl.	URAM	9335380	-4052682	2135	-462	19.14	-4.14	75.87	-2.99	2341	-413	20.98	-3.70
Ottawa Pl.	BLBR	3137986	-557338	685	-47	30.82	-2.12	66.85	-3.92	924	-26	41.55	-1.18
Ottawa Pl.	MAAM	1807935	154435	473	22	21.28	1.01	80.35	3.29	551	-9	24.77	-0.42
Ottawa Pl.	PLCI	3120276	-560941	671	-49	30.18	-2.19	64.14	-5.06	937	-14	42.17	-0.64
Ottawa Pl.	RASY	3639774	-216113	753	1	33.89	0.04	68.28	-2.78	999	26	44.95	1.18
Ottawa Pl.	SEAU	3147065	-556533	688	-49	30.96	-2.19	69.27	-2.62	901	-43	40.53	-1.92
Ottawa Pl.	STVA	3203250	-559328	723	-48	32.51	-2.17	71.19	-3.82	924	-26	41.55	-1.18

Ottawa Pl.	URAM	3090734	-574885	617	-62	27.74	-2.80	86.06	-3.97	645	-63	29.04	-2.83
Montérégie	BLBR	3061669	-451353	1043	-17	10.96	-0.18	48.72	-5.88	1763	103	18.53	1.09
Montérégie	MAAM	122200	-153307	68	-59	0.71	-0.62	14.63	-10.30	85	-66	0.89	-0.69
Montérégie	PLCI	3035636	-457852	1016	-23	10.67	-0.24	45.72	-7.48	1805	141	18.97	1.49
Montérégie	RASY	3144562	-447489	1063	-4	11.17	-0.04	48.00	-6.58	1807	139	18.99	1.46
Montérégie	SEAU	3074577	-449320	1049	-19	11.03	-0.20	53.05	-3.20	1681	41	17.66	0.44
Montérégie	STVA	3148773	-444395	1121	-7	11.78	-0.07	53.15	-5.47	1763	103	18.53	1.09
Montérégie	URAM	2446303	-445314	631	-25	6.63	-0.27	34.61	-4.55	679	2	7.14	0.02
Montréal	BLBR	20574	2414	15	2	2.36	0.35	46.30	-8.94	30	4	4.72	0.69
Montréal	MAAM	0.00	-220	0.00	-0.17	0.00	-0.03	0.00	-1.52	0.00	-0.18	0.00	-0.03
Montréal	PLCI	19429	1832	14	2	2.20	0.29	38.82	-11.23	32	6	5.07	0.94
Montréal	RASY	20655	2456	15	2	2.38	0.36	42.92	-9.66	31	5	4.94	0.85

Montréal	SEAU	21055	2656	15	2	2.38	0.36	58.97	0.68	27	3	4.23	0.41
Montréal	STVA	22923	3369	17	3	2.68	0.44	51.56	-7.61	30	4	4.72	0.69
Montréal	URAM	147	-7887	0.09	-2.60	0.01	-0.41	1.15	-5.63	0.09	-2.60	0.01	-0.41

[1] These results correspond to data shown in Figure 4a-d and Appendix S5a-d. For recent changes in landscape-level connectivity (**Δ**, 2011-2021), decreases are highlighted in red and increases highlighted in blue. MPC: metapopulation capacity, ECA: equivalent connected area index, based on the probability of connectivity index (PC), ECAf: ECA as % of the area in a region, ECA_{Ap}: fraction of habitat that is connected (ECA divided by the total amount of habitat area), as % of the area in a region, habitat area: species-specific area of habitat in the region, habitat area_f: species-specific habitat area as % of the area in a region. PLCI: Red-back salamander, RASY: Wood frog, STVA: Barred Owl, BLBR: Northern short-tailed shrew, SEAU: Ovenbird, MAAM: American marten, URAM: Black bear. Computation of total amounts of connectivity was done in each region by a simple multiplication of RE-Connect-derived landscape-level connectivity values with the area they cover in km^2 and consequent summation. Note that we scaled connectivity values by the area of the RE-Connect moving window size (8,700^2 = 75.69 km^2) prior to the summation if necessary, i.e. in the cases of MPC, ECA and habitat area. Species that meet a 30% area-based conservation target for ECA and habitat area are highlighted in yellow. See Table 1 for more details on connectivity indicators.

Appendix S7

Supporting Table 3. State (2021) and change (2011-2021) of patch-level forest connectivity for 7 ecoprofile species and 5 regions in the St-Lawrence Lowlands[1].

region	species	nr. patches 2021	BC mn±sd 2021	ND mn±sd 2021	MPCimp mn±sd 2021	ECAimp mn±sd 2021	Patch area (ha) mn±sd 2021	Δ nr. patches 2011-2021	Δ BC mn±se 2011-2021	Δ ND mn±se 2011-2021	Δ MPCimp mn±se 2011-2021	Δ ECAimp mn±se 2011-2021	Δ Patch area (ha) mn±se 2011-2021
Upper SL.Pl.	BLBR	11759	1.7±9.71	1.4±1.44	0.02±0.1	1.29±5.9	26.69±126.38	6627	1.11±0.1	0.39±0.02	-0.02±0	-1.32±0.13	-24.98±2.9
Upper SL.Pl.	MAAM	101	0.61±1.4	1.02±0.88	0.55±0.26	40.11±25.2	350.61±240.97	-33	0.04±0.17	0.09±0.12	0±0.03	-1.1±3.44	-46.48±37.54
Upper SL.Pl.	PLCI	30908	0±0	0.59±0.98	0.01±0.06	0.47±3.66	10.48±79.13	23575	NA	0.21±0.01	-0.02±0	-1.29±0.09	-25.95±1.93
Upper SL.Pl.	RASY	18568	2.9±18.66	1.72±1.78	0.02±0.08	0.83±4.8	17.72±106.61	12469	2.08±0.15	0.61±0.02	-0.02±0	-1.37±0.11	-26.23±2.42
Upper SL.Pl.	SEAU	4451	1.17±3.9	1.25±1.15	0.06±0.16	3.38±9.3	66.51±198.58	1034	0.61±0.07	0.19±0.02	-0.01±0	-0.55±0.23	-9.55±4.91
Upper SL.Pl.	STVA	11759	39.24±112.44	6.36±4.06	0.03±0.1	1.43±5.91	26.69±126.38	6627	26.43±1.14	2.44±0.05	-0.03±0	-1.46±0.13	-24.98±2.9
Upper SL.Pl.	URAM	65	0.07±0.13	0.42±0.4	0.78±0.14	68.07±23.6	1383.59±485.86	23	NA	0.2±0.07	-0.1±0.02	-22.22±3.85	-320.85±129.46
Middle SL.Pl.	BLBR	7962	2.49±11.46	1.63±1.59	0.02±0.1	1.22±6.32	39.07±198.79	5008	1.91±0.13	0.54±0.03	-0.02±0	-1.19±0.18	-35.01±5.43

Middle SL.Pl.	MAAM	289	0.89±1.58	1.36±0.9	0.44±0.25	28.39±21.01	540.89±484.5	-18	-0.16±0.14	-0.09±0.07	0.03±0.02	2.5±1.69	83.69±38.12
Middle SL.Pl.	PLCI	24512	0±0	0.73±1.19	0.01±0.05	0.38±3.62	13.1±115.02	20164	NA	0.34±0.01	-0.02±0	-1.2±0.12	-37.97±3.5
Middle SL.Pl.	RASY	11246	3.77±18.63	1.88±1.9	0.02±0.08	0.86±5.48	29.35±186.68	7758	3.02±0.18	0.73±0.03	-0.02±0	-1.16±0.15	-33.35±4.6
Middle SL.Pl.	SEAU	2821	1.97±5.61	1.54±1.23	0.06±0.16	3.41±10.24	104.97±322.28	726	1.16±0.12	0.25±0.03	0±0	0±0.3	2.77±9.13
Middle SL.Pl.	STVA	7962	55.97±130.03	6.76±4.08	0.03±0.1	1.33±6.38	39.07±198.79	5008	42.48±1.54	2.93±0.06	-0.02±0	-1.37±0.18	-35.01±5.43
Middle SL.Pl.	URAM	86	0.09±0.18	0.58±0.48	0.78±0.12	66.33±21.8	1606.52±783.62	38	0.01±0.04	0.02±0.09	-0.04±0.02	-9.69±3.8	-197.91±145.66
Ottawa Pl.	BLBR	1740	3.08±14.41	1.66±1.61	0.02±0.09	1.07±6.79	38.38±237.08	949	2.24±0.37	0.5±0.06	-0.01±0	-0.75±0.35	-27.67±12.12
Ottawa Pl.	MAAM	76	0.78±1.27	1.31±0.83	0.43±0.29	28.59±23.41	557.27±615.26	-8	-0.51±0.26	-0.21±0.14	0.09±0.05	6.55±3.52	97.23±87.54
Ottawa Pl.	PLCI	5028	0±0	0.68±1.14	0.01±0.06	0.36±4.01	13.59±140.66	3849	NA	0.24±0.03	-0.01±0	-0.82±0.22	-30.94±7.52
Ottawa Pl.	RASY	2596	4.44±21.22	1.97±1.88	0.01±0.08	0.67±5.44	25.79±200.63	1645	3.5±0.44	0.71±0.05	-0.01±0	-0.78±0.27	-28.48±9.28
Ottawa Pl.	SEAU	647	2.33±7.35	1.55±1.29	0.05±0.15	2.88±10.93	99.38±381.2	124	1.17±0.34	0.24±0.07	0±0.01	0.13±0.63	1.23±21.93
Ottawa Pl.	STVA	1740	56.68±128.16	6.96±4	0.03±0.09	1.16±6.82	38.38±237.08	949	36.73±3.45	2.42±0.13	-0.02±0	-0.84±0.35	-27.67±12.12

Ottawa Pl.	URAM	20	0.06±0.15	0.5±0.47	0.81±0.15	77.76±19.47	1989.92±924.52	8	0.01±0.05	-0.05±0.15	-0.04±0.05	-2.93±7.04	-275.11±334.5
Montérégie	BLBR	6021	1.25±8.42	1.27±1.32	0.02±0.1	1.32±6.03	24.34±121.76	3443	0.81±0.12	0.36±0.03	-0.03±0	-1.56±0.2	-25.04±3.88
Montérégie	MAAM	28	0.15±0.43	0.8±0.68	0.6±0.26	45.36±25.62	335.87±224.16	-11	-0.14±0.15	0.3±0.17	-0.04±0.07	-8.98±6.93	-29.53±64.06
Montérégie	PLCI	15092	0±0	0.54±0.92	0.01±0.07	0.5±3.84	9.99±77.78	11755	NA	0.21±0.01	-0.03±0	-1.64±0.14	-28.27±2.83
Montérégie	RASY	9362	2.08±14.57	1.55±1.59	0.02±0.08	0.85±4.89	16.12±100.93	6443	1.42±0.17	0.57±0.03	-0.03±0	-1.67±0.17	-27.38±3.35
Montérégie	SEAU	2312	0.88±3.07	1.13±1.08	0.06±0.16	3.44±9.43	59.79±191.24	530	0.49±0.07	0.17±0.03	-0.01±0.01	-0.76±0.32	-10.48±6.43
Montérégie	STVA	6021	29.08±95.33	5.77±3.6	0.03±0.1	1.46±6.02	24.34±121.76	3443	18.15±1.41	2.25±0.07	-0.03±0	-1.71±0.2	-25.04±3.88
Montérégie	URAM	32	0.06±0.13	0.49±0.36	0.76±0.15	63.3±25.05	1390.53±472.04	10	NA	0.22±0.09	-0.11±0.04	-21.77±6.3	-180.03±174.86
Montréal	BLBR	201	0.67±2.17	1.19±1.23	0.04±0.13	2.3±6.6	10.79±39.23	92	0.58±0.16	0.45±0.12	-0.02±0.02	-1.66±0.99	-4.76±4.18
Montréal	MAAM	0	NA	NA	NA	NA	NA	0	NA	NA	NA	NA	NA
Montréal	PLCI	644	0±0	0.38±0.67	0.01±0.08	0.68±3.64	3.68±22.4	434	NA	0.17±0.04	-0.02±0.01	-1.39±0.5	-4.63±1.92
Montréal	RASY	369	1.05±4.62	1.44±1.49	0.02±0.1	1.26±4.94	6.22±29.43	218	0.88±0.25	0.63±0.11	-0.02±0.01	-1.62±0.69	-5.22±2.79

Montréal	SEAU	63	0.55±1.27	1±1.11	0.13±0.22	6.98±11.07	30.03±66.45	15	NA	0.31±0.17	-0.01±0.04	-1.2±2.31	-2.65±10.5
Montréal	STVA	201	21.7±53.53	4.8±3.71	0.06±0.13	2.59±6.81	10.79±39.23	92	17.68±3.89	1.74±0.34	-0.02±0.02	-1.72±0.99	-4.76±4.18
Montréal	URAM	0	NA	NA	NA	NA	NA	0	NA	NA	NA	NA	NA

[1] These results correspond to data shown in Figure 4e-h and Appendix S5e-h. For recent changes in connectivity (**Δ**, 2011-2021), decreases are highlighted in red and increases highlighted in blue. To quantify recent change of connectivity indicators we used two-sided Welch t-tests in each region of interest. BC: betweenness centrality of a focal patch: the number of shortest paths between all other pairs of habitat patches in the landscape that go through the focal patch, ND: node degree of a focal patch: the number of other habitat patches connected to the focal patch, MPC$_{imp}$: metapopulation capacity patch importance, i.e. the contribution of a habitat patch to landscape-level metapopulation capacity, ECA$_{imp}$: equivalent connected area patch importance, i.e. the contribution of a habitat patch to landscape-level ECA, Patch area (ha): habitat patch area in hectares. See Table 1 for more details on connectivity indicators. mn: mean, sd: standard deviation, se: standard error of the mean estimated difference in the Welch t-tests. PLCI: Red-back salamander, RASY: Wood frog, STVA: Barred Owl, BLBR: Northern short-tailed shrew, SEAU: Ovenbird, MAAM: American marten, URAM: Black bear.

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