frontiers

Supplementary Material

DATA

In our research, we used the following datasets:

1. NMD, CadasterENV national land cover data (Swedish: Nationella Marktäckedata SWEREF 99 TM), basic layer, not generalized raster (nmd2018bas_ogeneraliserad_v1_0.tif) with spatial resolution of 10x10m, source: https://www.naturvardsverket.se/Sa-mar-miljon/Kartor/NationellaMarktackedata-NMD/Ladda-ned/

2. pCF, proxy Continuous Forest data, mapping of continuity forests in boreal region 2016 (Swedish: Kartering av Kontinuitetsskogar, SWEREF 99 TM), raster with spatial resolution of 10x10m, source: http://mdp.vicmetria.nu/miljodataportalen/

3. HCVF protected and non-protected - formally protected and non-protected forests of high conservation value, (Swedish: Skogliga värdekärnor), polygon-based shapefile, source: https://miljodataportalen.naturvardsverket.se/miljodataportalen/

4. Clearfelled areas (Swedish: Utförda avverkningar, Skogliga grunddata, SWEREF-99 TM, polygon-based shapefile, source: http://skogsdataportalen.skogsstyrelsen.se/Skogsdataportalen/

FOREST TYPES

In total, we used 14 different forest types, from the NMD, CadasterENV national land cover data, to produce input maps used in habitat suitability modelling. We assigned two possible habitat values (HV) to each type of forest: HV=1 (high habitat value), HV=0.5 (low habitat value) (Table A1). All other land cover classes in NMD were treated as non-habitat with assigned HV=0.

Names, codes in GIS and habitat value (HV):

1. Pine forest + Mixed coniferous forest (virtual species with natural pine-dominated forest as its main habitat)

- Pine forest not on wetland (code 111), HV = 1
- Pine forest on wetland (code 121), HV = 1
- Mixed coniferous not on wetland (code 113), HV = 0.5
- Mixed coniferous on wetland (code 123), HV = 0.5

2. Spruce forest + Mixed coniferous forest (virtual species with natural spruce-dominated forest as its main habitat)

- Spruce forest not on wetland (code 112), HV = 1
- Spruce forest on wetland (code 122), HV = 1
- Mixed coniferous not on wetland (code 113), HV = 0.5
- Mixed coniferous on wetland (code 123), HV = 0.5

3. Broadleaf forest classes (called "broadleaf" in NMD classification) + Coniferous forest with admixture of broadleaf trees (virtual species with natural broadleaf-dominated forest as its main habitat)

- Broadleaf forest not on wetland (code 115), HV = 1
- Broadleaf forest on wetland (code 125), HV = 1
- Broadleaf hardwood forest not on wetland (code 116), HV = 1
- Broadleaf hardwood forest on wetland (code 126), HV = 1
- Broadleaf forest with broadleaf hardwood forest not on wetland (code 117), HV = 1
- Broadleaf forest with broadleaf hardwood forest on wetland (code 127), HV = 1
- Mixed forest not on wetland (code 114), HV = 0.5
- Mixed forest on wetland (code 124), HV = 0.5

All three forest types were first converted to three separate rasters built upon merged HV (1.0 and 0.5) from four (pine and spruce) or eight (broadleaf) NMD classes. Two levels of conservation ambitions (Low demanding species (LD); High demanding species (HD)) were used as masks before landscape level analyses: 1. only formally protected forests (Protected Primary Forests = HCVFs protected) and formally protected forests plus other unprotected identified primary forests (All Primary Forests = combined HCVFs protected and HCVFs non-protected and pCFs). Data on recently clearfelled forest was used to update All Primary Forests.

HSI MODELS

Two contrasting levels of spatial requirements for virtual species were applied (LD and HD), to the three above-mentioned habitat types, thereby mimicking pine-, spruce- or broadleaf tree dependent organisms. This step is based on the idea of a minimum habitat area and the size of habitat at the landscape level (e.g., Manton et al., 2005). The effective habitat area, as defined by Orlikowska et al. (2020), is an area containing the habitat necessary to meet species' requirements. The habitat suitability index model parameter values (Table A1) are based on the species habitat requirements.

The effective habitat area was calculated by adding HV=1 (high habitat value) and HV=0.5 (low habitat value) i.e. 1 ha of HV=1 meant 1 ha of suitable habitat whereas the area of the HV=0.5 was divided by 2 following Edenius and Mikusiński (2012) in order to calculate the input of this stratum into effective habitat area.

Low demanding species (LD): small minimum habitat area (minimum 0.2 ha effective habitat area) and low landscape level requirements (minimum 5 % in 1 km^2 = 5 ha)

High demanding species (HD): large minimum habitat area (minimum 2 ha effective habitat area) and high landscape level requirements (minimum 20 % in 2 km^2 = 40 ha)

Before applying the above landscape filters, the habitat patches with effective area smaller than 0.2 ha for LD and 2 ha for HD, were removed (i.e. receive HV=0).

Low demanding species (LD) represent therefore an organism with good dispersal abilities being able to colonize relatively small and isolated habitat patches. High demanding species (HD) is an organism that requires larger contiguous patches of habitat and is not able to exist in highly fragmented landscape.

In total, six HSI-models were created - for two different virtual species (LD and HD) in three habitat types each (with pine-, spruce- or broadleaf trees) and applied for both levels of conservation ambitions (i.e. Protected Primary Forests and All Primary Forests).

In order to compute species-specific effective habitat area we ran our models entirely in ArcGIS environment (ESRI Inc., 2015), using species specific habitat suitability parameter values (Table A1).

For each species (LD and HD), we calculated the effective habitat area at two spatial scales: 1) individual pixels; 2) landscape scale. The spatial scale of individual pixels was defined as based solely on model parameters (Table A1) concerning 10 m x 10 m pixels and not taking into account the neighborhoods' habitat quality. As in Orlikowska et al. (2020), the landscape scale was defined by applying landscape filter selecting only those pixels that in addition to fulfilling habitat quality were also located in the areas that fulfilled species' requirements at the landscape level (Table A1).

First, we calculated pixel scale effective habitat area, in the form of raster maps, at the spatial scale of individual pixels, for the high habitat value (HV=1.0) representing good conditions, then low habitat value (HV=0.5) representing moderately good conditions (Table A1), which we then combined into one raster.

Secondly, the effective habitat at the landscape scale was calculated by applying species-specific measure of neighborhood using ArcGIS Focal Statistics tool (ESRI Inc., 2016) for a circular moving window with a radius of 564 m (100 ha) for LD and of 798 m (200 ha) for HD to the raster with pixel-level combined HV 1.0 and 0.5. Orlikowska et al. (2020) shows that the Focal Statistics tool (ESRI Inc., 2016) computed an output raster where the value for each output pixel was calculated as a sum of the input pixel values located within a species-specific circular moving window centered on that pixel.

Third, we identified pixels that are part of habitat networks at landscape scale consisting of 5 ha effective habitat area within a 100 ha window for LD, and 40 ha effective habitat area within a 200 ha window for HD.

Fourth, we calculated the landscape scale effective habitat area as the number of pixels for habitat value 1.0 and 0.5 that are located within the habitat networks identified in step three by overlaying the raster with identified habitat networks created in step three with the pixel scale raster maps made in step one containing habitat values 1.0 and 0.5, respectively. Next, the counties shapefiles were used to tabulate area for each habitat value within each county.

Table A1. Parameter values based on species habitat requirements used for creation of the habitat suitability models (Mikusiński and Edenius, 2006) applied to both levels of conservation ambitions Protected Primary Forests and All Primary Forests.

Parameters	**Species**	
	Low demanding species (LD)	**High demanding species (HD)**
Pixel scale requirements (10m x 10m)	**Habitat score 1.0**	**Habitat score 1.0**
Pine forest + Mixed coniferous forest	Pine forest not on wetland (code 111)	Pine forest not on wetland (code 111)
	Pine forest on wetland (code 121)	Pine forest on wetland (code 121)
Spruce forest + Mixed coniferous forest	Spruce forest not on wetland (code 112)	Spruce forest not on wetland (code 112)
	Spruce forest on wetland (code 122)	Spruce forest on wetland (code 122)
Broadleaf forest classes + Coniferous forest with admixture of broadleaf trees	Broadleaf forest not on wetland (code 115)	Broadleaf forest not on wetland (code 115)
	Broadleaf forest on wetland (code 125)	Broadleaf forest on wetland (code 125)
	Broadleaf hardwood forest not on wetland (code 116)	Broadleaf hardwood forest not on wetland (code 116)
	Broadleaf hardwood forest on wetland (code 126)	Broadleaf hardwood forest on wetland (code 126)
	Broadleaf forest with broadleaf hardwood forest not on wetland (code 117)	Broadleaf forest with broadleaf hardwood forest not on wetland (code 117)
	Broadleaf forest with broadleaf hardwood forest on wetland (code 127)	Broadleaf forest with broadleaf hardwood forest on wetland (code 127)
Pixel scale requirements (10m x 10m)	**Habitat score 0.5**	**Habitat score 0.5**
Pine forest + Mixed coniferous forest	Mixed coniferous not on wetland (code 113)	Mixed coniferous not on wetland (code 113)
	Mixed coniferous on wetland (code 123)	Mixed coniferous on wetland (code 123)
Spruce forest + Mixed coniferous forest	Mixed coniferous not on wetland (code 113)	Mixed coniferous not on wetland (code 113)
	Mixed coniferous on wetland (code 123)	Mixed coniferous on wetland (code 123)
Broadleaf forest classes + Coniferous forest with admixture of broadleaf trees	Mixed forest not on wetland (code 114)	Mixed forest not on wetland (code 114)
	Mixed forest on wetland (code 124)	Mixed forest on wetland (code 124)
Landscape scale requirements		
Habitat networks	≥ 5.0 ha	≥ 40 ha
Neighbourhood window size	100 ha	200 ha

Table A2. Area (in ha) and number of networks per subregion and patch size class for pine-dominated forests, separated into protected and all primary forest and for species with high and low demands.

Pine forest								
Study regions	Protected primary forest				All primary forest			
Patch size classes	Low demands		High demands		Low demands		High demands	
	Area	Networks	Area	Networks	Area	Networks	Area	Networks
Class < 10 ha								
Norrbotten west	725	514	167	44	1921	1363	678	223
Norrbotten east	77	43	24	8	1945	1249	1210	399
Västerbotten west	183	133	19	13	1432	896	133	59
Västerbotten east	38	14	27	8	2463	1308	941	306
Jämtland	166	87	9	5	2638	1591	442	133
Västernorrland	22	9	21	8	1630	854	367	122
Dalarna	73	43	15	14	1597	1075	860	288
Gävleborg	82	29	19	3	1478	844	576	195
Class 10 to < 100 ha								
Norrbotten west	12945	266	3457	76	26781	550	11769	253
Norrbotten east	5590	99	1546	35	18402	388	21720	482
Västerbotten west	4191	84	551	9	22591	486	3797	78
Västerbotten east	4937	77	1022	22	28178	573	19438	448
Jämtland	7303	138	1096	19	43305	899	12933	270
Västernorrland	4001	66	464	10	30616	617	7862	162
Dalarna	4748	82	1503	35	10881	253	15382	337
Gävleborg	4999	78	741	15	13893	309	9699	220
Class 100 to < 1000 ha								
Norrbotten west	104970	338	59989	162	147929	527	151872	456
Norrbotten east	71171	199	28607	92	118394	388	181797	603
Västerbotten west	30623	93	5040	18	121583	445	33827	112
Västerbotten east	32628	131	7655	30	140607	502	115027	430
Jämtland	38435	148	7826	27	222149	810	86403	301
Västernorrland	27699	96	2681	9	175780	582	60330	199
Dalarna	57138	203	20976	72	61325	216	120773	399
Gävleborg	25990	92	7173	23	71029	261	70889	231
Class 1000 to < 10,000 ha								
Norrbotten west	258662	78	77817	39	202127	69	180209	87
Norrbotten east	72960	33	5176	4	109647	46	124421	59
Västerbotten west	26166	11	1659	1	212413	72	21450	12
Västerbotten east	27541	13	3425	3	194638	84	78366	43
Jämtland	46178	23	9577	4	237142	99	82752	39
Västernorrland	8559	3	4783	3	292368	108	39171	22
Dalarna	74300	27	34702	21	83711	29	127737	54
Gävleborg	21603	9	1036	1	90436	34	37699	20
Class > 10,000 ha								
Norrbotten west	307668	14	15592	1	1537138	7	90028	5
Norrbotten east	12236	1	7037	1	1876657	7	0	0
Västerbotten west	15841	1	0	0	215240	4	0	0
Västerbotten east	0	0	0	0	1347920	11	0	0
Jämtland	27875	2	0	0	1000731	14	33210	2
Västernorrland	0	0	0	0	473107	18	0	0
Dalarna	97159	4	15554	1	1852915	4	70962	4
Gävleborg	0	0	0	0	956312	8	0	0

Table A3. Area (in ha) and number of networks per subregion and patch size class for spruce-dominated forests, separated into protected and all primary forest and for species with high and low demands.

	Spruce forest							
Study regions /	Protected primary forest				All primary forest			
Patch size classes	Low demands		High demands		Low demands		High demands	
	Area	Networks	Area	Networks	Area	Networks	Area	Networks
Class < 10 ha								
Norrbotten west	428	254	172	78	2025	1199	492	181
Norrbotten east	93	46	71	20	3357	1728	334	113
Västerbotten west	49	28	31	15	979	497	347	126
Västerbotten east	68	18	3	3	3224	1513	244	80
Jämtland	142	83	45	22	2751	1461	981	342
Västernorrland	37	10	9	1	2040	1008	478	135
Dalarna	196	80	55	16	2889	1457	337	104
Gävleborg	46	14	7	4	2232	1172	110	34
Class 10 to < 100 ha								
Norrbotten west	8561	168	4559	95	27081	585	12089	250
Norrbotten east	4854	78	2029	38	52623	1066	6881	161
Västerbotten west	3406	57	993	19	16562	313	6274	137
Västerbotten east	6193	95	1204	22	58428	1157	6326	131
Jämtland	10593	182	2216	42	39514	792	21774	473
Västernorrland	3302	58	731	17	29072	596	11994	259
Dalarna	10098	168	1877	36	41556	869	6110	139
Gävleborg	4631	77	590	10	37772	756	2607	68
Class 100 to < 1000 ha								
Norrbotten west	48819	165	63147	179	140721	496	105392	318
Norrbotten east	58508	180	15206	55	284510	1000	41957	167
Västerbotten west	26267	65	26433	71	92938	309	53576	154
Västerbotten east	38430	145	9251	37	354207	1245	31974	137
Jämtland	54123	184	23381	70	253072	834	185978	612
Västernorrland	31612	108	7824	34	181941	611	61781	248
Dalarna	55908	215	16213	51	219848	767	42398	163
Gävleborg	25199	96	3855	18	212984	704	10644	56
Class 1000 to < 10,000 ha								
Norrbotten west	133815	41	169660	59	194357	89	217209	77
Norrbotten east	70341	21	31590	15	302265	134	41750	20
Västerbotten west	103077	34	52411	15	143069	48	84290	27
Västerbotten east	17483	10	1175	1	334799	148	11754	7
Jämtland	83801	29	39825	16	283195	117	189335	79
Västernorrland	10839	5	2123	2	218604	87	19030	11
Dalarna	77659	23	12639	8	288354	115	30223	13
Gävleborg	9991	7	0	0	249718	101	0	0
Class > 10,000 ha								
Norrbotten west	778272	13	156019	6	1673248	8	276563	12
Norrbotten east	33836	3	0	0	587614	14	10949	1
Västerbotten west	124159	4	70491	3	847971	8	333806	8
Västerbotten east	0	0	0	0	141422	8	0	0
Jämtland	140299	3	61768	3	1777074	24	139547	5
Västernorrland	0	0	0	0	647899	11	0	0
Dalarna	25477	2	0	0	587709	13	0	0
Gävleborg	0	0	0	0	166471	7	0	0

Table A4. Area (in ha) and number of networks per subregion and patch size class for broadleaf-dominated forests, separated into protected and all primary forest and for species with high and low demands.

	Broadleaf forest							
Study regions /	Protected primary forest				All primary forest			
Patch size classes	Low demands		High demands		Low demands		High demands	
	Area	Networks	Area	Networks	Area	Networks	Area	Networks
Class < 10 ha								
Norrbotten west	1019	711	87	263	3099	2040	385	154
Norrbotten east	179	74	0	0	1917	1213	59	15
Västerbotten west	202	129	53	24	821	511	112	42
Västerbotten east	62	28	6	1	2382	1127	6	1
Jämtland	210	206	49	12	1917	1213	176	58
Västernorrland	12	6	0	0	1183	563	0	0
Dalarna	250	148	0	0	1190	585	0	0
Gävleborg	60	14	0	0	1350	649	0	0
Class 10 to < 100 ha								
Norrbotten west	14838	323	7391	146	49314	1042	10654	233
Norrbotten east	4831	96	173	5	30576	666	1354	35
Västerbotten west	4138	79	2290	48	15884	323	2693	60
Västerbotten east	2239	47	146	2	37108	814	155	2
Jämtland	5331	108	740	16	30576	666	2210	46
Västernorrland	1374	23	0	0	19394	426	0	0
Dalarna	6166	115	111	4	20989	441	206	5
Gävleborg	2117	39	129	3	21086	470	60	2
Class 100 to < 1000 ha								
Norrbotten west	110310	335	66238	197	263704	914	98830	317
Norrbotten east	25637	102	421	2	96362	361	2992	13
Västerbotten west	33695	105	15114	46	59468	225	19911	57
Västerbotten east	8561	41	105	1	107004	457	248	2
Jämtland	36462	112	9151	29	96362	361	25711	85
Västernorrland	2251	15	0	0	37638	180	0	0
Dalarna	25071	99	349	2	55865	240	357	2
Gävleborg	10632	42	181	1	55906	233	330	2
Class 1000 to < 10,000 ha								
Norrbotten west	214243	80	91022	39	289439	116	152187	58
Norrbotten east	2093	2	0	0	166178	59	0	0
Västerbotten west	53181	20	16396	7	66184	28	10474	4
Västerbotten east	2610	2	0	0	39256	24	0	0
Jämtland	65560	29	7013	4	166178	59	46823	16
Västernorrland	0	0	0	0	5612	4	0	0
Dalarna	30653	10	0	0	36948	11	0	0
Gävleborg	2434	1	0	0	9978	5	0	0
Class > 10,000 ha								
Norrbotten west	729748	15	140827	6	1422568	15	279435	5
Norrbotten east	0	0	0	0	453124	8	0	0
Västerbotten west	356046	5	203475	6	678251	2	360705	3
Västerbotten east	0	0	0	0	0	0	0	0
Jämtland	97305	4	0	0	453124	8	0	0
Västernorrland	0	0	0	0	0	0	0	0
Dalarna	0	0	0	0	10067	1	0	0
Gävleborg	0	0	0	0	0	0	0	0

REFERENCES

Edenius, L., Mikusiński, G., 2012. Framework for building models for species habitat suitability assessment in the biodiversity module of Heureka system.

https://www.heurekaslu.se/help/en/index.html?habitatmodels.htm.

ESRI Inc., 2015. ArcGIS 10.3.1 for Desktop, Redlands, CA: Environmental Systems Research Institute.

ESRI Inc., 2016. How focal Statistics works ArcMap 10.3 http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-focal-statistics-works.htm

Manton, M., Angelstam, P., and Mikusiński, G. (2005). Modelling habitat suitability for deciduous forest focal species – a sensitivity analysis using different satellite land cover data. *Landscape Ecol.* 20, 827-839. doi: 10.1007/s10980-005-3703-z

Mikusiński, G. and Edenius, L. (2006). Assessment of spatial functionality of old forest in Sweden as habitat for virtual species. Scand. J. Forest Res. 21 (Suppl. 7), 73-83. doi: 10.1080/14004080500487045

Orlikowska, E. H., Svensson, J., Roberge, J. -M., Blicharska, M., Mikusiński, G. (2020). Hit or miss? Evaluating the effectiveness of Natura 2000 for conservation of forest bird habitat in Sweden. Global Ecol. Conserv. 22:00939. doi: 10.1016/j.gecco.2020.e00939