Supplemental Material

Population Abundance and Ecosystem Service Provision: the Case of Birds

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Appendix S1. Statistical Analysis

Cultural Services - Visitors to nature reserves.

Total bird abundances were calculated from the UK's Wetland Bird Survey (WeBS) and Visitor numbers were provided by the WWT for the 10 years between 2005 and 2014. As most of the birds using the nature reserves are winter migrants we only considered data from October to March (whilst the dataset was mostly complete, there were a few months missing for some centres). As visitor numbers are affected by the weather (B. Hughes, pers. comm.) we included weather data obtain from the nearest Met Office historical station to each of the Wetland Centre's into the models. Weather data included were mean daily maximum temperature, mean daily minimum temperature, number of air frost days, total rainfall and total sunshine duration.

For all Wetland Centre's, visitor numbers (logarithmically transformed) were modelled using general linear mixed effect models with bird abundance and the weather variables as predictors and Wetland Centre location as a random factor. Linear, logarithmic and polynomial models were fitted and the best fit selected based on R^2 using the methods of Nakagawa and Schielzeth (2013). Predictors were standardized using the 'arm' package and model simplification was achieved by comparing all subsets of the global model using AIC and retaining all models within dAIC<6 of the top model. Where multiple models were retained model averaging was used to produce final parameter estimates and the relative importance of each model (Table S1e).

As the various Wetland Centre's are all quite different, visitor numbers were also modelled separately for each Centre using general linear models. Model selection and simplification were carried out as for the 'All Centre's' model (Table S1e).

Other Services

Linear, logarithmic, 2nd order polynomial, asymptotic models were produced for all data sets. Asymptotic models were based on the Michaelis-Menten equation and modelled using the self-starting 'nls' model in the 'stats' package. The best model for selection based on model fit using the coefficient of determination (R^2) and model parsimony using AIC. In all cases the best model had the highest R^2 and lowest AIC.

Asymptotic model from Jackson et al. 2008. All calculations and analyses where carried out in the R language and environment for statistical computing (v3.3.0).

References

Jackson AL, Ruxton DG, Houston DC. 2008. The effect of social facilitation on foraging success in vultures: a modelling study. Biology Letters 4: 311-313.

Nakagawa S, Schielzeth H. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution 4: 133-142.

R Development Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing. http://www.R-project.org, Vienna, Austria.

Table S1: Statistical results and model selection data for; a) Nutrient transport, b) Seed dispersal, c) Scavenging, d) Pest control, e) Cultural: bird count and visitor numbers, f) Mental health, g) Dis-service: crop damage. B1 = first parameter. Vm = Maximum rate (Michaelis-Menten equation). B1CI low = lower confidence interval for the first parameter. B1CI high = higher confidence interval for the first parameter. B2 = second parameter (polynomial models). K= point at which abundance is half of the asymptote. B2 CI low = lower confidence interval for the second parameter. B2 CI high = lower confidence interval for the second parameter.

a) Nutrient Transport

Penguins **(Lindeboom 1984)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	6	8.55E-01	7.67E-06	-9.28E-07	1.63E-05	NA	NA	NA	0.507	1.21	13.4
Polynomial	6	9.73E-02	1.96E-05	-1.56E-04	1.95E-04	-3.64E-11	-5.73E-10	5.00E-10	0.352	1.19	15.3
Logarithmic	6	-1.14E+01	1.14E+00	-1.52E-01	2.43E+00	NA	NA	NA	0.500	1.23	13.5
Asymptotic	6	NA	1.89E+05	6.63E+04	NA	4.82E+00	2.33E+00	NA	NA	1.22	13.4

Geese **(Kitchell et al. 1999)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	15	-1.19E+02	8.79E-03	4.36E-03	1.32E-02	NA	NA	NA	0.554	77277	177
Polynomial	15	8.22E+01	-1.05E-02	-2.46E-02	3.65E-03	3.91E-07	1.13E-07	6.69E-07	0.729	43342	170
Logarithmic	15	-1.21E+03	1.31E+02	2.72E+01	2.35E+02	NA	NA	NA	0.310	118578	183

Crows **(Fujita and Koike 2009)**

Model	***n***	***Intercept***	***B1 / Vm***	***B1 CI low***	***B1 CI high***	***B2 / K***	***B2 CI low***	***B2 CI high***	***R2***	***dev***	***AIC***
Linear	55	-1.82E-01	2.87E-04	2.54E-04	3.19E-04	NA	NA		0.854	7.14E+02	303
Polynomial	55	-3.59E-01	3.28E-04	1.98E-04	4.58E-04	-2.70E-10	-1.10E-09	5.56E-10	0.853	7.08E+02	305
Logarithmic	55	-2.15E+01	3.18E+00	1.97E+00	4.40E+00	NA	NA		0.330	3.28E+03	387
Asymptotic	Failed to Converge										

b) Seed Dispersal

Seed Dispersal 1 **(García et al. 2010)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	83	4.46E-01	6.93E-03	4.92E-03	8.93E-03	NA	NA	NA	0.361	3.39	-23.8
Polynomial	83	3.50E-01	1.79E-02	1.16E-02	2.41E-02	-1.45E-04	-2.24E-04	-6.60E-05	0.445	2.91	-34.6
Log	83	2.32E-01	1.46E-01	1.12E-01	1.81E-01	NA	NA	NA	0.458	2.88	-37.5
Asymptotic	83	NA	8.70E-01	7.67E-01	9.93E-01	4.77E+00	2.71E+00	7.87E+00	NA	3.03	-33.2

Seed Dispersal 2 **(García and Martínez 2012)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	89	3.97E-01	1.51E-02	9.27E-03	2.10E-02	NA	NA	NA	0.223	5.67	13.52
Polynomial	89	3.24E-01	4.34E-02	3.08E-02	5.59E-02	-5.47E-04	-7.69E-04	-3.26E-04	0.386	4.43	-6.48
Logarithmic	89	4.15E-01	1.32E-01	1.04E-01	1.59E-01	NA	NA	NA	0.504	3.62	-26.46
Asymptotic	89	NA	8.31E-01	7.13E-01	9.70E-01	1.15E+00	6.52E-01	1.94E+00	NA	3.71	-24.32

Seed Dispersal 3 **(Martínez and García 2017)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	87	3.82E-01	9.10E-03	3.02E-03	1.52E-02	NA	NA	NA	0.084	4.84	1.49
Polynomial	87	3.39E-01	4.31E-02	1.68E-02	6.94E-02	-6.95E-04	-1.22E-03	-1.70E-04	0.143	4.47	-3.42
Logarithmic	87	4.21E-01	9.21E-02	5.85E-02	1.26E-01	NA	NA	NA	0.250	3.96	-15.98
Asymptotic	87	NA	5.80E-01	4.78E-01	7.18E-01	2.82E-01	1.07E-01	6.46E-01	NA	4.1	-12.85

c) Scavenging

Vultures **(This study)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	49	5.68E+02	-4.30E+00	-7.10E+00	-1.49E+00	NA	NA	NA	0.150	2655750	679
Polynomial	49	8.09E+02	-1.35E+01	-2.22E+01	-4.78E+00	6.65E-02	6.56E-03	1.26E-01	0.217	2395986	676
Logarithmic	49	1.39E+03	-2.75E+02	-4.18E+02	-1.33E+02	NA	NA	NA	0.228	2414325	675
Asymptotic	49	NA	1.64E+02	1.25E+02	2.13E+02	-1.66E+01	-1.75E+01	-1.48E+01	NA	1775619	659

Crows **(Inger et al. 2016)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	62	1.52E+02	6.80E-03	3.26E-03	1.03E-02	NA	NA	NA	0.184	634028	754
Polynomial	62	1.28E+02	1.94E-02	9.41E-03	2.95E-02	-5.82E-07	-1.02E-06	-1.47E-07	0.260	565292	749
Logarithmic	62	7.28E+01	2.01E+01	1.49E+01	2.53E+01	NA	NA	NA	0.489	396631	725
Asymptotic	62	NA	2.49E+02	2.26E+02	2.72E+02	3.22E+00	1.68E+00	6.96E+00	NA	343399	716

d) Pest Control

Insectivores **(Maas et al. 2015)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	10	-1.82E+00	2.62E-01	8.27E-02	4.41E-01	NA	NA	NA	0.535	1.55E+02	62
Polynomial	10	-8.95E+00	6.16E-01	-1.82E-01	1.41E+00	-3.58E-03	-1.14E-02	4.27E-03	0.545	1.33E+02	62
Logarithmic	10	-3.08E+01	1.10E+01	4.07E+00	1.79E+01	NA	NA	NA	0.579	1.40E+02	61
Asymptotic	Failed to Converge										

Insectivores **(Crawford and Jennings 1989)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	R^2	*Deviance*	*AIC*
Linear	22	-1.03E+02	1.65E+04	1.13E+04	2.17E+04	NA	NA	NA	0.673	2.87E+08	429

Polynomial	22	3.15E+01	1.58E+04	4.48E+02	3.12E+04	4.75E+02	-1.01E+04	1.11E+04	0.656	2.87E+08	431
Logarithmic	22	NA	1.38E+04	1.01E+04	1.76E+04	6.05E+03	3.42E+03	8.69E+03	NA	4.30E+08	438
Asymptotic	Failed to Converge										

e) Cultural: bird count and visitor numbers

Model fitting results to establish the relationship between bird abundance and visitors number to WWT Wetland Centre's whilst considering weather variables. All centres models are general linear mixed effect models, with centre as a random variable. Other models are linear models. Most parsimonious model is highlighted in bold. Parameter estimates and statistics refer to the most parsimonious model.

Winter Data	Models	df	AIC	R2(m)	R2(c)	Parameter	Estimate	Std. Error	z value	p value	
All Centres	Linear	9	238.63	0.01	0.89	Intercept	8.6172	0.2841	30.2430	<0.001	***
	Logarithmic	**9**	**221.75**	**0.01**	**0.89**	Frost days	-0.0088	0.0028	3.1230	0.0018	**
	Polynomial	10	285.88	0.15	0.89	Rain	-0.0010	0.0003	3.6000	<0.001	***
Individual Centre's				**R2**							
Arundel	Linear	8	-5.65	0.28		Intercept	8.5979	0.0278	302.9730	<0.001	***
	Logarithmic	**8**	**-5.79**	**0.28**		Frost days	-0.0989	0.0664	1.4560	0.1454	
	Polynomial	9	-4.32	0.27		Sunshine	0.2497	0.0657	3.7250	<0.001	***
						Rainfall	-0.0675	0.0646	1.0230	0.3062	
						Mean Min. Temp	0.0676	0.1329	0.4980	0.6181	
						Mean Max Temp	0.0299	0.1507	0.1950	0.8456	
						Bird Abundance	-0.0194	0.0597	0.3170	0.7513	
Caverlaverock	Linear	8	8.16	0.29		Intercept	7.4053	0.2860	25.5300	<0.001	***
	Logarithmic	**8**	**8.15**	**0.29**		Rainfall	-0.0013	0.0004	2.8560	0.0043	**
	Polynomial	9	10.11	0.28		Mean Min. Temp	0.0596	0.0258	2.2590	0.0239	*

					Sunshine	0.0017	0.0018	0.9340	0.3502	
					Mean Max Temp	0.0273	0.0363	0.7420	0.4578	
					Frost days	-0.0090	0.0147	0.6020	0.5471	
					Bird Abundance	0.0016	0.0406	0.0380	0.9698	
Castle Espie	Linear	8	19.02	0.31	Intercept	7.3120	0.5836	12.3740	<0.001	***
	Logarithmic	**8**	**17.68**	**0.32**	Mean Max Temp	0.1394	0.0628	2.1930	0.0283	*
	Polynomial	9	18.15	0.32	Mean Min. Temp	-0.1069	0.0569	1.8480	0.0646	.
					Bird Abundance	-0.0853	0.0657	1.2670	0.2053	
					Frost days	-0.0032	0.0156	0.1990	0.8425	
					Sunshine	0.0030	0.0033	0.9030	0.3666	
					Rainfall	0.0000	0.0011	0.0320	0.9743	
Llanell	Linear	8	-6.27	0.51	Intercept	8.4618	0.2070	38.6590	<0.001	***
	Logarithmic	**8**	**-6.49**	**0.52**	Frost days	-0.0449	0.0116	3.6660	<0.001	***
	Polynomial	9	-4.27	0.48	Rainfall	-0.0037	0.0011	3.3300	0.0009	***
					Mean Min. Temp	-0.0345	0.0404	0.8080	0.4194	
					Sunshine	0.0008	0.0010	0.7600	0.4474	
					Bird Abundance	0.0214	0.0407	0.4930	0.6220	
					Mean Max Temp	0.0191	0.0455	0.4010	0.6881	
London	**Linear**	**8**	**-44.51**	**0.41**	Intercept	9.4002	0.0201	457.8190	<0.001	***
	Log**arithmic**	8	-42.81	0.39	Frost days	0.1264	0.0699	1.7700	0.0768	.
	Polynomial	9	-43.30	0.41	Bird Abundance	-0.1487	0.0482	3.0240	0.0025	**
					Mean Max Temp	0.4368	0.1894	2.2800	0.0226	*
					Mean Min. Temp	-0.2264	0.1767	1.2630	0.2067	
					Sunshine	0.0722	0.1025	0.6950	0.4873	
					Rainfall	-0.0188	0.0451	0.4080	0.6832	

Martin Mere	Linear	8	19.17	0.02	Intercept	10.4097	0.7749	50.3610	<0.001	***
	Logarithmic	**8**	**18.54**	**0.03**	Bird Abundance	-0.1223	0.0682	1.2910	0.0788	.
	Polynomial	9	19.82	0.02	Mean Max Temp	-0.0461	0.0412	0.4660	0.2679	
					Mean Min. Temp	0.0041	0.0021	0.7620	0.0584	.
					Frost days	0.0153	0.0157	0.3080	0.3342	
					Rainfall	-0.0006	0.0009	0.2230	0.4907	
					Sunshine	0.0020	0.0016	1.7580	0.1993	
Slimbridge	Linear	8	1.60	0.09	Intercept	9.9557	0.4390	22.4330	<0.001	***
	Logarithmic	**8**	**1.29**	**0.10**	Mean Max Temp	-0.0207	0.0213	0.9580	0.3380	
	Polynomial	9	3.07	0.09	Sunshine	-0.0010	0.0008	1.2610	0.2070	
					Bird Abundance	-0.0612	0.0483	1.2400	0.2150	
					Mean Min. Temp	0.0053	0.0344	0.1510	0.8800	
					Frost days	0.0076	0.0093	0.8070	0.4200	
					Rainfall	0.0004	0.0008	0.4860	0.6270	
Washington	**Linear**	**8**	**37.35**	**0.11**	Intercept	8.4140	0.3971	24.5830	<0.001	***
	Logarithmic	8	37.80	0.10	Bird Abundance	0.0000	0.0001	0.4360	0.5153	
	Polynomial	9	39.35	0.89	Mean Max Temp	-0.0138	0.0177	0.4530	0.4383	
					Mean Min. Temp	-0.0025	0.0011	0.2810	0.0349	*
					Frost days	-0.0096	0.0208	1.6320	0.6469	
					Rainfall	-0.0008	0.0011	0.6820	0.4982	
Welney	Linear	8	45.47	0.15	Intercept	6.1349	0.8526	6.9640	<0.001	***
	Logarithmic	**8**	**43.28**	**0.20**	Bird Abundance	0.2140	0.0809	2.5520	0.0100	**
	Polynomial	9	45.41	0.17	Mean Min. Temp	0.0031	0.0015	1.9750	0.0483	*
					Rainfall	-0.0017	0.0025	0.6340	0.5260	
					Sunshine	-0.0008	0.0022	0.3700	0.7111	
					Mean Max Temp	-0.0048	0.0203	0.2310	0.8174	

						Frost days		-0.0133	0.0247	0.5240	0.6004

f) Mental health

Depression **(Cox et al. 2017)**

Model	n	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	*R-sq*	*Deviance*	*AIC*
Linear	225	8.08E+00	-1.06E-02	-1.93E-02	-1.85E-03	NA	NA	NA	0.0206	5978	1382
Polynomial	225	8.75E+00	-1.56E-02	-5.90E-02	2.78E+02	8.77E-06	8.29E-05	-6.53E-05	0.0164	5976	1384
Logarithmic	225	1.97E+01	-2.61E+00	-4.86E+00	-3.50E-01	NA	NA	NA	0.0183	5991	1383
Asymptotic	225	NA	4.16E+00	3.24E+00	5.65E+00	-4.97E+01	1.33E+01	-7.80E+01	NA	6054	1385

Anxiety **(Cox et al. 2017)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	*R-sq*	*Deviance*	*AIC*
Linear	225	6.70E+00	-9.92E-03	01.72E-02	-2.67E-03	NA	NA	NA	0.0273	4111	1298
Polynomial	225	6.34E+00	-7.14E-03	-4.31E-02	2.88E-02	-4.85E-06	6.55E-05	-6.63E-05	0.023	4111	1300
Logarithmic	225	1.71E+01	-2.34E+00	-4.22E+00	-4.69E-01	NA	NA	NA	0.0221	4133	1299
Asymptotic	225	NA	3.22E+00	2.48E+00	4.43E+00	-4.90E+01	1.69E+01	-7.83E+01	NA	4196	1303

Stress **(Cox et al. 2017)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	*R-sq*	*Deviance*	*AIC*
Linear	225	7.20E+00	-9.53E-03	-1.76E-02	-1.48E-03	NA	NA	NA	0.0195	5069	1345
Polynomial	225	6.29E+00	-2.65E-03	-4.26E-02	3.73E-02	-1.20E-05	5.62E-05	-8.02E-05	0.0156	5067	1347
Logarithmic	225	1.69E+01	-2.21E+00	-4.29E+00	-1.30E-01	NA	NA	NA	0.0149	5093	1346
Asymptotic	225	NA	3.22E+00	2.48E+00	4.43E+00	-4.90E+01	1.69E+0.1	-7.83E+01	NA	4196	1303

g) Disservice: crop damage

Damage **(Canavelli et al. 2014)**

Model	*n*	*Intercept*	*B1 / Vm*	*B1CI low*	*B1CI high*	*B2 / K*	*B2CI low*	*B2CI high*	*R-sq*	*Deviance*	*AIC*
Linear	49	1.36E+00	1.47E-01	3.43E-02	2.60E-01	NA	NA	NA	0.1092	531	262
Polynomial	49	2.49E-01	5.24E-01	2.63E-01	7.85E-01	-1.32E-02	-2.17E-02	4.83E-03	0.2527	436	254
Logarithmic	49	1.19E+00	1.44E+00	6.44E-01	2.24E+00	NA	NA	NA	0.2029	475	256
Asymptotic	49	NA	4.78E+00	1.08E+00	2.01E+01	6.87E+00	4.33E+00	1.27E+01	NA	469	256

Figure S1. Further case studies of relationships between bird abundance and ecosystem service provision. From left to right, the top row shows supporting services (nutrient transport for penguins; seed dispersal 2 and 3); mid row shows regulating services (pest control); bottom row shows cultural services (all reserves (no relationship found), lower levels of depression). See Tables 1 and S1 for details.