Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change – SUPPLEMENTARY MATERIAL

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(a) Source of bird data and limitations

The Rare Breeding Birds Panel collates information submitted by ornithologists on breeding by a specified set of bird species in the United Kingdom (UK) and compiles a standard annual report. Information is mainly contributed by amateur ornithologists through county bird recorders but is supplemented, for some species, by records from wardens of nature reserves and, in some years, by special surveys of particular species, including those organised or conducted by professionals. Many of the records are the result of opportunistic discoveries of rare birds by amateur ornithologists, followed up by subsequent checking and monitoring. Because the data are not the outcome of a standardised, systematic programme of fieldwork, it is impossible to say what proportion of the true population of each species is detected and reported. We believe it likely that, on average, this proportion has increased over the years included in our analysis because birdwatchers have become more numerous and wide-ranging and because the number of professionals who contribute data (e.g. nature reserve wardens) has also increased. Hence, we do not claim that the trends in reported numbers presented in this paper measure the true trend in numbers: we believe that the true trend will usually be more negative than that reported. However, we suggest that trends over time in detection and reporting probability are broadly similar for the species considered, and therefore that the variation among species in trends in reported numbers will be strongly correlated with that of trends in true population.

(b) Selection of species

We wished to restrict our analysis to terrestrial birds and therefore excluded the one seabird in the database, *Sterna dougallii*. We excluded *Loxia pytyopsittacus* because the effort and ability of observers to distinguish it from *L. curvirostra* and *L. scotica* has changed too markedly during the study period for us to take its apparent population trend as being comparable with those of the other species. We excluded all eight species of raptors (Accipitriformes and Falconiformes) from the analysis because of marked changes in status that were clearly caused by factors other than climatic change; their populations have been recovering after alleviation of the earlier adverse effects of direct persecution and/or pesticide contamination (Newton 1979). Two of these species (*Haliaetus albicilla* and *Milvus milvus*) also have expanding populations in the UK derived from recent reintroductions. We excluded the duck *Bucephala clangula*, which only rarely uses natural nest sites in the UK, because its breeding population has been strongly affected by special efforts to provide nestboxes. Although some of the other species are considered to have benefited from conservation management (Aebischer, Green & Evans 2000), we considered that the effects on their population trends were unlikely to have been as marked as those considered above and retained them in the analysis.

We also excluded from further analysis the eight species (*Gavia immer*, *Himantopus himantopus*, *Tringa ochropus*, *Larus minutus*, *Upupa epops*, *Luscinia svecica*, *Eremophila alpestris* and *Hippolais icterina*) for which the average number of pairs (or equivalent) recorded per year for the period 1980 – 2004 was below one pair per year, because we believed the data for these were too sparse for the calculation of a meaningful population trend. The remaining 42 species are listed in table S1.

Of the 42 species listed and used in our analyses, one species appears as an outlier on Figure 2(a) and 2(b). We would exclude such an outlier if there was reason to believe that the unusual measured value may be due to an undetected measurement error. However, the outlying species was *Egretta garzetta*, a large, conspicuous, easily-identified species that has colonised parts of the UK where there are many birdwatchers. Hence, we consider it very unlikely that its observed population trend has been measured incorrectly. Nonetheless, we explored the effect of this species on our results by computing the simple standardised regression coefficient between POPT and CST after excluding *E. garzetta*. Exclusion of *E. garzetta* changed the regression coefficients and their statistical significance in different directions according to whether or not the 11 species with mean population levels of less than 5 pairs were also excluded ($\beta = 0{\cdot}162$, $p = 0{\cdot}1558$ for all species except *E. garzetta*; $\beta = 0{\cdot}486$, $p = 0{\cdot}0032$ for species with mean populations of more than 5 pairs except *E. garzetta*; cf. β and p values in Table 1). Smaller effects of excluding *E. garzetta* were found for the regression of POPT on LAT ($\beta = -0{\cdot}304$, $p = 0{\cdot}0267$ for all species except *E. garzetta*; $\beta = -0{\cdot}386$, $p = 0{\cdot}0176$ for species with mean populations of more than 5 pairs except *E. garzetta*). Hence, although we believe that the datum for *E. garzetta* should be retained for the reasons given above, our results remain broadly similar if it is excluded.

(c) Mean latitude of the European range

We calculated the mean of the latitude of the centres of each 50-km UTM square in which a species was simulated to occur under 1961 – 1990 mean climate conditions using the climate response surface (CRS) model fitted to the European Bird Census Council distribution data (Hagemeijer & Blair 1997; Huntley *et al.* 2007). This latitude was similar to that obtained by averaging the latitudes of the squares in which a species was recorded. However, we considered the mean latitude of the simulated range superior because it allows, to some extent, for incomplete coverage of eastern Europe. This covariate (LAT) is expressed in degrees of north latitude.

(d) Mean body mass, breeding habitat and migratory behaviour

We obtained data on body mass in grams from Dunning (1993). Where he gives information for males and females separately, we averaged them. We took the natural logarithm of mean body mass (LMS) as the covariate in our analyses.

We based our habitat classification (HAB) upon that of Tucker and Evans (1997), but simplified it to reduce its nine categories to three and adapted it so that it referred to the breeding season only. We used accounts of habitat in Snow & Perrins (1997) and Hagemeijer & Blair (1997) to adapt the classification. In particular, we assigned *Cygnus cygnus*, *Aythya marila*, *Anas acuta*, *Anas querquedula*, *Melanitta nigra*, *Grus grus*, *Limosa, limosa*, *Calidris temminckii*, *Philomachus pugnax*, *Tringa glareola* and *Phalaropus lobatus* to the wetland category on the basis of the emphasis given in these accounts to pools, marshes and other damp habitats as important components of the breeding habitat. Although we initially intended to have a separate category for birds of agricultural land, only three species would have been so classified, so we included these in the open habitat category. The three habitat classes were: (1) wetland, comprising coastal and inland wetlands; (2) open habitats, comprising tundra, shrubland, rocky habitats, agricultural land and grassland; and (3) forest, comprising boreal and temperate forests.

We classified species according to their migratory behaviour (MIG) in western Europe, as mapped by Snow & Perrins (1997). Our three categories were: (1) resident; (2) partial and short distance migrants with >50% of the population remaining within the western Palearctic region in winter; and (3) long distance migrants with >50% of the population moving beyond the western Palearctic region in winter. We assigned *Limosa limosa* to the long distance migrant category because, of the two subspecies with widely separated main breeding distributions that breed in the UK, the trans-Saharan migrant, *L. l. limosa*, predominates.

(e) Proximity to the UK of other parts of the European breeding range of a species

We calculated a measure of proximity to the UK (PRX) of 50-km UTM squares outside the UK from which a species was recorded as present in the atlas of Hagemeijer & Blair (1997) by obtaining the sum of the reciprocals of the geodesic distances (in km) between the centres of all such occupied squares and the centre of a given 50-km in the UK. We then averaged this measure across all UTM squares in the UK.

(f) Climate data

The bioclimate variables used in our analysis were derived from a compilation of meteorological data for the period 1970 – 2002 (Mitchell & Jones 2005). We interpolated values for monthly mean temperatures, mean monthly precipitation and monthly mean proportion of potential sunshine received (‘cloudiness’) for the geographic mid-point of each of the 50-km UTM grid squares with more than half of its area in the UK. The bioclimatic variables were then calculated for each square in each calendar year from these data using the approach and software developed by Prentice *et al*. (1992) and previously applied and described by Huntley *et al*. (1995).

We calculated climate suitability trends as means for the entire UK and used these in the analyses reported. However, these national trends might not be representative of trends in the part of the country occupied by a species, or most likely to be colonised by a species because of proximity to its continental range. In order to explore the extent to which this might affect our results we repeated our analyses using mean climatic suitability trends calculated separately for the north and south of the UK. For this purpose we divided the UTM grid squares along the grid line at *ca*. 53° N extending from Anglesey to Lincolnshire. We allocated each species to one of three categories: (1) at least two-thirds of breeding records in the south of the UK; (2) at least two-thirds of records in the north of the UK; (3) others. We then used the climate suitability trend calculated for the appropriate half of the UK for each species, using the CST for the whole of the UK for category (3) species. Doing this had little effect on the simple correlation coefficients between POPT and CST (r = 0·219 (0·242) for all species; r = 0·461 (0·478) for species with mean populations greater than 5 pairs; values in brackets for national mean trends). We therefore present the results for the national mean climate suitability trends (Table 1).

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Table S1. Bird species analysed, the units in which they were counted (BP – breeding pairs, CBP – confirmed breeding pairs, M – males, MXP – maximum pairs, MXT – maximum territories, NB – nests and broods, P – pairs, SM – singing males), years in which data were excluded because of poor or good coverage and years in which good coverage by national systematic surveys was allowed for in the regression model.

Common name	Scientific name	Units	Excluded: poor	Excluded: good	Modelled: good
Red-necked grebe	*Podiceps grisegena*	MXP			
Slavonian grebe	*Podiceps auritus*	BP			
Black-necked grebe	*Podiceps nigricollis*	MXP			
Bittern	*Botaurus stellaris*	SM			
Little egret	*Egretta garzetta*	MXP			
Spoonbill	*Platalea leucorodia*	MXP			
Whooper swan	*Cygnus cygnus*	MXP			
Pintail	*Anas acuta*	MXP			
Garganey	*Anas querquedula*	MXP			
Pochard	*Aythya ferina*	MXP			
Scaup	*Aythya marila*	MXP			
Common scoter	*Melanitta nigra*	MXP		1995	
Quail	*Coturnix coturnix*	MXP			
Spotted crake	*Porzana porzana*	SM		1999	
Crane	*Grus grus*	P	2001		
Avocet	*Recurvirostra avosetta*	CBP	2001		
Stone curlew	*Burhinus oedicnemus*	CBP	2001		1987–2004
Temminck's stint	*Calidris temminckii*	MXP			
Purple sandpiper	*Calidris maritima*	MXP			
Ruff	*Philomachus pugnax*	NB			
Black-tailed godwit	*Limosa limosa*	MXP			
Wood sandpiper	*Tringa glareola*	MXP			
Red-necked phalarope	*Phalaropus lobatus*	M			
Mediterranean gull	*Larus melanocephalus*	MXP			
Wryneck	*Jynx torquilla*	MSM			
Woodlark	*Lullula arborea*	MXT	2001		1986, 1997
Black redstart	*Phoenicurus ochruros*	MXP	2001		2000, 2002
Fieldfare	*Turdus pilaris*	MXP			
Redwing	*Turdus iliacus*	MXP			
Cetti's warbler	*Cettia cetti*	MXP	2001	1996	
Savi's warbler	*Locustella luscinioides*	MXP			
Marsh warbler	*Acrocephalus palustris*	MXP			
Dartford warbler	*Sylvia undata*	MXP	2001		1974, 1984, 1994
Firecrest	*Regulus ignicapillus*	MXP			
Bearded tit	*Panurus biarmicus*	BP	2001		1992, 2002
Golden oriole	*Oriolus oriolus*	MXP			
Red-backed shrike	*Lanius collurio*	MXP			
Brambling	*Fringilla montifringilla*	MXP			
Serin	*Serinus serinus*	MXP			
Scarlet rosefinch	*Carpodacus erythrinus*	MXP			
Snow bunting	*Plectrophenax nivalis*	MXP			
Cirl bunting	*Emberiza cirlus*	MXP	1999, 2001		1989–1993, 1998, 2003

Table S2. Observed population trend (POPT), climate suitability trend (CST), mean latitude of the European range (LAT) and nuisance variable values (see ESM text and Materials and Methods) for the 42 bird species analysed.

species	HAB	MIG	PRX	LMS	LAT	CST	POPT
Podiceps grisegena	wet	short	0·368	6·93	52·36	-0·16795	0·06546
Podiceps auritus	wet	short	0·230	6·12	60·20	-0·08267	-0·02732
Podiceps nigricollis	wet	short	0·450	5·68	48·91	-0·04437	0·04565
Botaurus stellaris	wet	short	0·574	6·82	50·76	-0·05098	-0·01363
Egretta garzetta	wet	long	0·185	6·21	44·91	0·02420	0·46140
Platalea leucorodia	wet	long	0·052	7·55	45·15	-0·05944	0·22420
Cygnus cygnus	wet	short	0·253	9·14	63·78	0·03886	0·10710
Anas acuta	wet	short	0·399	6·92	60·11	-0·02933	0·01281
Anas querquedula	wet	long	0·958	5·79	52·62	-0·04339	0·01811
Aythya ferina	wet	short	0·905	6·71	51·75	-0·00446	0·05093
Aythya marila	wet	short	0·197	6·85	65·90	-0·18319	0·02676
Melanitta nigra	wet	short	0·203	6·86	66·20	0·00082	-0·04977
Coturnix coturnix	open	long	1·286	4·57	48·06	-0·01975	0·03519
Porzana porzana	wet	long	0·730	4·36	52·61	-0·07128	0·04935
Grus grus	wet	short	0·491	8·61	57·58	-0·23704	0·07456
Recurvirostra avosetta	wet	short	0·208	5·72	47·80	-0·04761	0·08505
Burhinus oedicnemus	open	short	0·380	6·13	42·74	0·00216	0·05376
Calidris temminckii	wet	long	0·097	3·14	66·40	-0·12154	-0·02144
Calidris maritima	open	short	0·129	4·40	67·99	-0·13189	0·00041
Philomachus pugnax	wet	long	0·417	4·92	60·67	-0·09961	-0·06561
Limosa limosa	wet	long	0·460	5·67	52·32	-0·04274	-0·00182
Tringa glareola	wet	long	0·367	4·21	60·66	-0·04847	0·05765
Phalaropus lobatus	wet	long	0·192	3·52	65·54	0·02899	0·01902
Larus melanocephalus	wet	short	0·082	5·55	47·10	-0·02479	0·17520
Jynx torquilla	forest	long	1·394	3·51	52·83	-0·09484	-0·08468
Lullula arborea	open	short	1·160	3·29	47·75	-0·02601	0·08627
Phoenicurus ochruros	open	short	1·246	2·80	47·74	-0·01751	-0·03473
Turdus pilaris	open	short	1·057	4·66	56·39	-0·10727	-0·01771
Turdus iliacus	forest	short	0·563	4·11	59·79	-0·08011	-0·05566
Cettia cetti	wet	resident	0·532	2·66	41·92	0·04868	0·08203
Locustella luscinioides	wet	long	0·627	2·71	48·79	-0·01464	-0·06530
Acrocephalus palustris	open	long	0·967	2·42	51·56	-0·06818	-0·04904
Sylvia undata	open	resident	0·353	2·38	41·88	0·04504	0·07986
Regulus ignicapillus	forest	short	0·857	1·72	46·69	-0·01795	0·03878
Panurus biarmicus	wet	short	0·300	2·75	48·11	0·01296	-0·00887
Oriolus oriolus	forest	long	1·321	4·37	49·24	-0·04778	-0·02016
Lanius collurio	open	long	1·400	3·40	51·06	-0·09776	-0·09683
Fringilla montifringilla	forest	short	0·393	3·18	62·09	-0·11719	-0·06298
Serinus serinus	open	short	1·172	2·42	46·01	-0·00956	-0·08187
Carpodacus erythrinus	open	long	0·579	3·18	56·43	-0·21929	0·03576
Plectrophenax nivalis	open	short	0·174	3·74	67·45	-0·06720	0·01581
Emberiza cirlus	open	resident	0·640	3·14	42·71	0·02560	0·08792