Vertebrate population trends are influenced by interactions between land use, climatic position, habitat loss and climate change.

Supplementary information

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Appendix 1: Land-use categories

Table S1: The 37 land-cover classes classified by the European Space Agency Climate Change Initiative (ESA CCI; ESA Land Cover CCI project team, Defourny, 2019), and the land-use categories we grouped them into for our analysis (closely following the groupings used by the Intergovernmental Panel on Climate Change for change detection; Defourny et al., 2017). The classes were also grouped (with a weighting system) to form a semi-natural habitat (SNH) category, in order to calculate change in land use surrounding populations. In this weighting system, we used the maximum percentage cover of a specific land use (detailed in the ESA's land-use categories) to weight each category (for example, the category 'Tree cover, broadleaved, deciduous, closed to open (>15%)' was given a weighting of 1, as it could cover 100% of the 300 × 300-m area, whereas the category 'Tree cover, broadleaved, deciduous, open (15-40%)' was given a weighting of 0.4, as this could cover a maximum of 40% of the 300 × 300-m area). Non-SNH categories were given a weighting of 0.

The land-use category used in our analysis	**Land cover classification system used in the ESA CCI land-cover maps▲**			**Included as semi-natural habitat? (Y/N)**	**Weighting system**
Agriculture	10		Rainfed cropland	N	0
		11	Herbaceous cover	N	0
		12	Tree or shrub cover	N	0
	20		Irrigated cropland	N	0
	30		Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	N	0

	40		Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	N	0
	100^{+}		Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	N	0
Forest	50		Tree cover, broadleaved, evergreen, closed to open (>15%)	Y	1
	60		Tree cover, broadleaved, deciduous, closed to open (>15%)	Y	1
		61	Tree cover, broadleaved, deciduous, closed (>40%)	Y	1
		62	Tree cover, broadleaved, deciduous, open (15-40%)	Y	0.4
	70		Tree cover, needleleaved, evergreen, closed to open (>15%)	Y	1
		71	Tree cover, needleleaved, evergreen, closed (>40%)	Y	1
		72	Tree cover, needleleaved, evergreen, open (15-40%)[WJ1]	Y	0.4
	80		Tree cover needleleaved, deciduous, closed to open (>15%)	Y	1
		81	Tree cover, needleleaved, deciduous, closed (>40%)	Y	1
		82	Tree cover, needleleaved, deciduous, open (15-40%)	Y	0.4
	90		Tree cover, mixed leaf type (broad leaved and needleleaved)	Y	1
	160		Tree cover, flooded, fresh or brackish water	Y	1
	170		Tree cover, flooded, saline water	Y	1
Grassland	110		Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	Y	0.5
	130		Grassland	Y	1
Wetland	180		Shrub or herbaceous cover, flooded, fresh-saline or brackish water	Y	1
Urban	190		Urban	N	0
Other	120		Shrubland	Y	1

		121	Evergreen shrubland	Y	1
		122	Deciduous shrubland	Y	1
	140		Lichens and mosses	N	0
	150		Sparse vegetation (tree, shrub, herbaceous cover)	N	0
		152	Sparse shrub (<15%)	N	0
		153	Sparse herbaceous cover (<15%)	N	0
	200		Bare areas	N	0
		201	Consolidated bare areas	N	0
		202	Unconsolidated bare areas	N	0
Water*	210		Water	N	0
Snow and ice*	220		Permanent snow and ice	N	0

* We did not consider these categories in our analysis, so removed populations starting in these areas.

$^{+}$ This was classed as agriculture due to personal communications with members of the Sentinel (Social and Environmental Trade-Offs in African Agriculture) Project (www.sentinel-gcrf.org), who have found that this land-use category was commonly cropland with sparse trees.

▲ The 37^{th} class is a No Data class.

Appendix 2: Map of populations

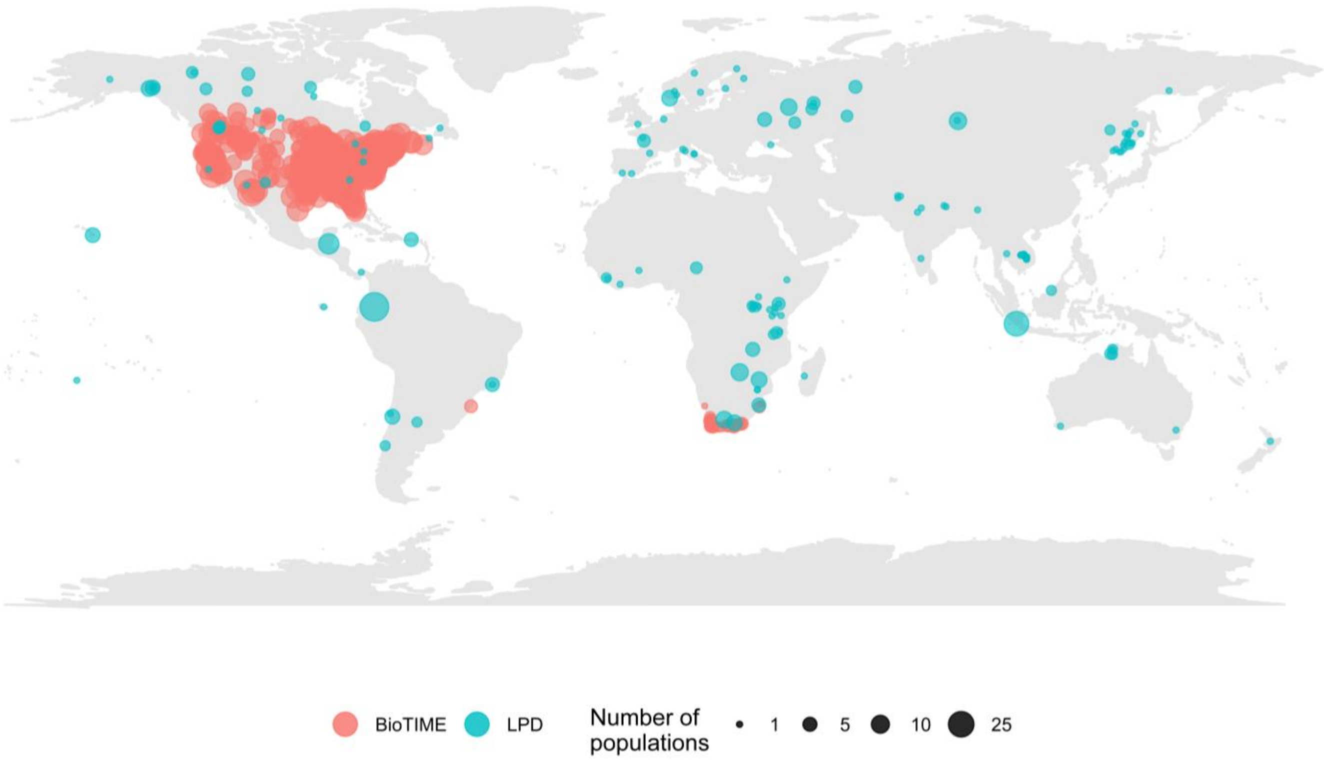

Figure S1: The location of terrestrial vertebrate populations included in the final dataset. The size reflects the number of populations at that location, with colours differentiating the Living Planet dataset (LPD) and BioTIME dataset.

Appendix 3: Further information on methods and results

Model selection

Based on our hypotheses and the aims of this study, we constructed 42 candidate models (table S3). Table S2 lists the variables included in the candidate models.

Table S2: The variables that were considered in our candidate models. See the main text for further details on each variable.

Term	Variable
Main effects	Starting land-use type Rate of change in semi-natural habitat Starting climatic position, with respect to a) maximum temperature of the warmest month (T_{max}) b) minimum temperature of the coldest month (T_{min}) c) precipitation of the wettest month (Pp_{max}) d) precipitation of the driest month (Pp_{min}) Rate of change in climate, with respect to a) maximum temperature of the warmest month b) minimum temperature of the coldest month c) precipitation of the wettest month d) precipitation of the driest month
Interactions	Three types of 3-way interactions A) starting land-use type × rate of change in SNH × starting climatic position B) starting land-use type × starting climatic position × rate of change in climate (with the same focal climatic variable as the climatic position) C) starting land-use type × rate of change in SNH × rate of change in climate Plus all the lower order interactions nested within these 3-way interactions.
Covariates	Distance to range edge Distance to range edge × starting land-use type Distance to range edge × rate of change in SNH Distance to range edge × starting land-use type × rate of change in SNH
Random effects	Species name Class Study site Database

To produce the selection of candidate models (table S3), we first produced a null model (including only the intercept and random effects; Model 1 in table S3), and a full model (including all the variables in table S2, with rate of change in surrounding semi-natural habitat, rates of change in climate, and starting climatic positions fit as quadratic terms, and distance to range edge fit as a linear term; see the main text for the reasoning behind choosing the three-way interactions; Model 2). Following this, we produced 11 further models, each time taking the full model and excluding one set of variables (main effects or covariates, and all their associated interactions): we removed (1) starting land-use type (Model 3), (2) rate of change in semi-natural habitat (Model 4), (3) each starting climatic position (Models 5-8), (4) each rate of climate change variable (Models 9-12) and (5) distance to range edge (Model 13). We then produced five further models, each time removing a different climatic variable group: we removed (1) rate of change in maximum temperature of the warmest month and starting T_{max} position (Model 14), (2) rate of change in minimum temperature of the coldest month and starting T_{min} position (Model 15), (3) rate of change in precipitation of the wettest month and starting Pp_{max} position (Model 16) , (4) rate of change in precipitation of the driest month and starting Pp_{min} position (Model 17) and (5) all rates of change in precipitation variables and starting Pp_{max} and Pp_{min} position (Model 18). Then, to assess the importance of interactions, we produced a model that only included the main effects and distance to range edge measure (and no interactions; Model 19). Further, we constructed a model that only included the 2-way interactions from the full model, to determine the impact of including the 3-way interactions that we had hypothesised (Model 20). As detailed in the main text, due to our hypotheses, we focused on three types of 3-way interactions (type A, B, and C in the table above). To evaluate the importance of each type of interaction and investigate which may be more important in influencing rates of population change, we constructed six further models, including each combination of the three types of 3-way interactions (Models 21-26). Then, we produced 12 further models, each time excluding an individual 3-way interaction (Models 27-38). Finally, to assess the importance of the quadratic terms we included in the model, we ran four further models that included all the same variables as the full model, but in which either all continuous variables were fit as linear terms (Model 39), the rate of change in semi-natural habitat was fit as a linear term (Model 40), the rates of change in climate were fit as linear terms (Model 41) or starting climatic positions were fit as linear terms (Model 42). Table S3 lists the selection of candidate models and gives the AIC value, weighted Akaike, and marginal R^2 values for each model, with one model (the full model) performing much better than the rest, and as such, selected as the final model and reported in the main text.

Table S3: The 42 candidate models constructed to investigate how the rate of population change is affected by land-use type and change, a population's climatic position, and the rate of climate change experienced. After using AIC, Akaike weights, and marginal R^2 values to compare models, there was a clear best-performing model (Model 2, in bold in the table). ΔAIC values (to one decimal place) are given in comparison to the best-performing model. See table S2 for a reminder of all the variables considered.

Model	**ΔAIC**	**Akaike Weight**	**Marginal R^2**
Null model			
(1) A null model (which contained only the intercept and random effects).	1198.7	0.00	0.000
Full model			
(2) A full model, containing all main effects, covariates, the three types of 3-way interaction as described in the main text, and the lower order interactions nested within the 3-way interactions.	**0.0**	**1.00**	**0.048**
Removing each variable, one at a time			
(3) A model with all terms in, except those including starting land-use type.	991.9	0.00	0.019
(4) A model with all terms in, except those including rate of change in semi-natural habitat.	921.5	0.00	0.030
(5) A model with all terms in, except those including starting T_{max} position.	207.1	0.00	0.040
(6) A model with all terms in, except those including starting T_{min} position.	228.7	0.00	0.044
(7) A model with all terms in, except those including starting Pp_{max} position.	177.9	0.00	0.046
(8) A model with all terms in, except those including starting Pp_{min} position.	223.1	0.00	0.042
(9) A model with all terms in, except those including rate of change in maximum temperature of the warmest month.	200.6	0.00	0.040

(10) A model with all terms in, except those including rate of change in minimum temperature of the coldest month.	243.7	0.00	0.044
(11) A model with all terms in, except those including rate of change in precipitation of the wettest month.	210.0	0.00	0.047
(12) A model with all terms in, except those including rate of change in precipitation of the driest month.	227.4	0.00	0.044
(13) A model with all terms in, except those including the population's distance to its species' range edge.	32.8	0.00	0.047
Removing climatic variable groups			
(14) A model with all terms in, except those including the rate of change in maximum temperature of the warmest month or a population's starting T_{max} position.	295.4	0.00	0.036
(15) A model with all terms in, except those including the rate of change in minimum temperature of the coldest month or a population's starting T_{min} position.	324.9	0.00	0.041
(16) A model with all terms in, except those including the rate of change in precipitation of the wettest month or a population's starting Pp_{max} position.	281.7	0.00	0.045
(17) A model with all terms in, except those including the rate of change in precipitation of the driest month or a population's starting Pp_{min} position.	328.5	0.00	0.042
(18) A model with all terms in, except those including rate of change in precipitation of the wettest or driest month, or a population's starting Pp_{max} or Pp_{min} position.	592.8	0.00	0.036
Removing interactions			
(19) A model containing all the main effects and distance to range edge measure, but no interactions.	1253.6	0.00	0.010

(20) A model containing all the main effects, the 2-way interactions included in the full model, but no 3-way interactions.	1118.5	0.00	0.030
(21) A model containing all the main effects, covariates, the type A 3-way interactions (see above), and the lower order interactions nested within these interactions (i.e., starting land-use type × rate of change in semi-natural habitat, starting land-use type × starting climatic position, and rate of change in semi-natural habitat × starting climatic position).	867.8	0.00	0.025
(22) A model containing all the main effects, covariates, the type B 3-way interactions, and the lower order interactions nested within these interactions (i.e., starting land-use type × rate of change in climate, starting land-use type × starting climatic position, and starting climatic position × rate of change in climate).	876.1	0.00	0.031
(23) A model containing all the main effects, covariates, the type C 3-way interactions, and the lower order interactions nested within these interactions (i.e., starting land-use type × rate of change in semi-natural habitat, starting land-use type × rate of change in climate, and rate of change in semi-natural habitat × rate of change in climate).	812.3	0.00	0.030
(24) A model containing all the main effects, covariates, the type A and B 3-way interactions, and the lower order interactions nested within these.	477.4	0.00	0.038
(25) A model containing all the main effects, covariates, the type A and C 3-way interactions, and the lower order interactions nested within these.	460.3	0.00	0.038
(26) A model containing all the main effects, covariates, the type B and C 3-way interactions, and the lower order interactions nested within these.	410.6	0.00	0.045

(27) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and a population's starting T_{max} position.	80.0	0.00	0.047
(28) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and a population's starting T_{min} position.	80.4	0.00	0.047
(29) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and a population's starting Pp_{max} position.	84.7	0.00	0.046
(30) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and a population's starting Pp_{min} position.	97.6	0.00	0.047
(31) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in maximum temperature of the warmest month and a population's starting T_{max} position.	80.6	0.00	0.045
(32) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in minimum temperature of the coldest month and a population's starting T_{min} position.	109.7	0.00	0.046
(33) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in precipitation of the wettest month and a population's starting Pp_{max} position.	78.5	0.00	0.047
(34) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in precipitation of the driest month and a population's starting Pp_{min} position.	91.4	0.00	0.047
(35) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and rate of change in maximum temperature of the warmest month.	99.5	0.00	0.046
(36) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and rate of change in minimum temperature of the coldest month.	91.7	0.00	0.046

(37) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and rate of change in precipitation of the wettest month.	111.2	0.00	0.045
(38) A model with all terms in, except the 3-way interaction between starting land-use type, rate of change in semi-natural habitat and rate of change in precipitation of the driest month.	92.6	0.00	0.047
Including linear, rather than quadratic, terms			
(39) A full model, including all variables in table S2, but with the rate of change in semi-natural habitat, rate of change in climate and starting climatic positions fit as linear terms (i.e., no quadratic terms were included in the model).	1015.7	0.00	0.022
(40) A full model, including all variables in table S2, but with the rate of change in semi-natural habitat fit as a linear term.	496.3	0.00	0.040
(41) A full model, including all variables in table S2, but with the rates of change in climate fit as linear terms.	460.9	0.00	0.036
(42) A full model, including all variables in table S2, but with the starting climatic positions fit as linear terms.	419.1	0.00	0.040

Further information on the results

Table S4: The correlations (Spearman correlation, *p*) between the continuous variables considered. These variables were: average annual rate of change in semi-natural habitat (SNH_rate), starting climatic positions with regard to T_{max} (Tmax_pos), T_{min} (Tmin_pos), Pp_{max} (Ppmax_pos) and Pp_{min} (Ppmin_pos), average annual rate of change in climate with regard to maximum temperature of the warmest month (MaxT_rate), minimum temperature of the coldest month (MinT_rate), precipitation of the wettest (MaxP_rate) and driest (MinP_rate) months, and distance to range edge (Stand_dist).

	SNH_rate	Tmax_pos	Tmin_pos	Ppmax_pos	Ppmin_pos	MaxT_rate	MinT_rate	MaxP_rate	MinP_rate	Stand_dist
SNH_rate										
Tmax_pos	-0.027									
Tmin_pos	0.002	0.331								
Ppmax_pos	-0.025	0.325	-0.032							
Ppmin_pos	0.015	0.193	-0.013	0.461						
MaxT_rate	-0.025	-0.257	-0.146	-0.249	-0.433					
MinT_rate	0.034	-0.337	-0.355	-0.156	-0.070	0.094				
MaxP_rate	0.065	-0.073	-0.057	-0.126	0.238	-0.218	0.188			
MinP_rate	0.062	-0.424	-0.243	-0.101	-0.279	0.125	0.337	0.176		
Stand_dist	-0.071	0.209	0.013	0.127	0.091	0.104	-0.129	-0.230	-0.216	

Table S5: The fixed-effects included in the final model. The model included the land-use type the population was within in the first year of recording (starting land-use type), the average annual rate of change in semi-natural habitat (SNH) in a 1-km radius surrounding the population, a population's distance from their range edge (a standardised measure, see main text), a population's starting climatic positions with regard to maximum temperature of the warmest month (T_{max} position), minimum temperature of the coldest month (T_{min} position), and precipitation of the wettest (Pp_{max} position) and driest months (Pp_{min} position), and the average annual rate of change in climate with regard to maximum temperature of the warmest month, minimum temperature of the coldest month, and the precipitation of the wettest and driest month. All continuous variables in the model, apart from distance to range edge, were run as second-degree (i.e., quadratic) orthogonal polynomials. Distance to range edge was run as a first-degree (i.e., linear) orthogonal polynomial.

Fixed-effects	**Term**	
Main effects	Starting land-use type	Starting Pp_{min} position
	Rate of change in SNH	Rate of change in maximum temperature
	Distance to range edge	Rate of change in minimum temperature
	Starting T_{max} position	Rate of change in precipitation of the wettest month
	Starting T_{min} position	Rate of change in precipitation of the driest month
	Starting Pp_{max} position	
Two-way interactions	Starting land-use type × distance to range edge	Rate of change in SNH × starting Pp_{min} position
	Starting land-use type × rate of change in SNH	Rate of change in SNH × rate of change in maximum temperature
	Starting land-use type × starting T_{max} position	Rate of change in SNH × rate of change in minimum temperature
	Starting land-use type × starting T_{min} position	Rate of change in SNH × rate of change in precipitation of the wettest month
	Starting land-use type × starting Pp_{max} position	Rate of change in SNH × rate of change in precipitation of the driest month
	Starting land-use type × starting Pp_{min} position	
	Starting land-use type × rate of change in maximum temperature	
	Starting land-use type × rate of change in minimum temperature	

	Starting land-use type × rate of change in precipitation of the wettest month	Rate of change in maximum temperature × starting T_{max} position
	Starting land-use type × rate of change in precipitation of the driest month	Rate of change in minimum temperature × starting T_{min} position
	Rate of change in SNH × distance to range edge	Rate of change in precipitation of the wettest month × starting Pp_{max} position
	Rate of change in SNH × starting T_{max} position	Rate of change in precipitation of the driest month × starting Pp_{min} position
	Rate of change in SNH × starting T_{min} position	
	Rate of change in SNH × starting Pp_{max} position	
Three-way interactions	Starting land-use type × rate of change in SNH × starting T_{max} position	Starting land-use type × rate of change in precipitation of the wettest month × starting Pp_{max} position
	Starting land-use type × rate of change in SNH × starting T_{min} position	Starting land-use type × rate of change in precipitation of the driest month × starting Pp_{min} position
	Starting land-use type × rate of change in SNH × starting Pp_{max} position	Starting land-use type × rate of change in SNH × rate of change in maximum temperature
	Starting land-use type × rate of change in SNH × starting Pp_{min} position	Starting land-use type × rate of change in SNH × rate of change in minimum temperature
	Starting land-use type × rate of change in SNH × distance to range edge	Starting land-use type × rate of change in SNH × rate of change in precipitation of the wettest month
	Starting land-use type × rate of change in maximum temperature × starting T_{max} position	Starting land-use type × rate of change in SNH × rate of change in precipitation of the driest month
	Starting land-use type × rate of change in minimum temperature × starting T_{min} position	

Table S6: The 10th, 50th and 90th percentiles of the continuous explanatory variables included in the final dataset. Tmax, Tmin, Ppmax and Ppmin position refer to a population's starting climatic positions with regard to maximum temperature of the warmest month, minimum temperature of the coldest month, and precipitation of the wettest and driest months, respectively.

Continuous explanatory variables	Percentiles		
	10th	50th	90th
Average annual rate of change in semi-natural habitat (% / year)	-1.20	0.02	1.07
Starting climatic position			
Tmax position	0.73	0.82	0.91
Tmin position	0.19	0.32	0.44
Ppmax position	0.09	0.20	0.56
Ppmin position	0.004	0.03	0.08[WJ2]
Average annual rate of change in climate			
Maximum temperature of the warmest month (°C / year)	-0.04	0.04	0.20
Minimum temperature of the coldest month (°C / year)	-0.07	-0.003	0.13
Precipitation of the wettest month (monthly mm / year)	-4.33	-0.59	3.19
Precipitation of the driest month (monthly mm / year)	-1.70	-0.26	0.64
Distance from range edge	0.02	0.17	0.62

The following three figures (S2-4) present an alternative way of displaying the results presented in the main text in figures 4-6.

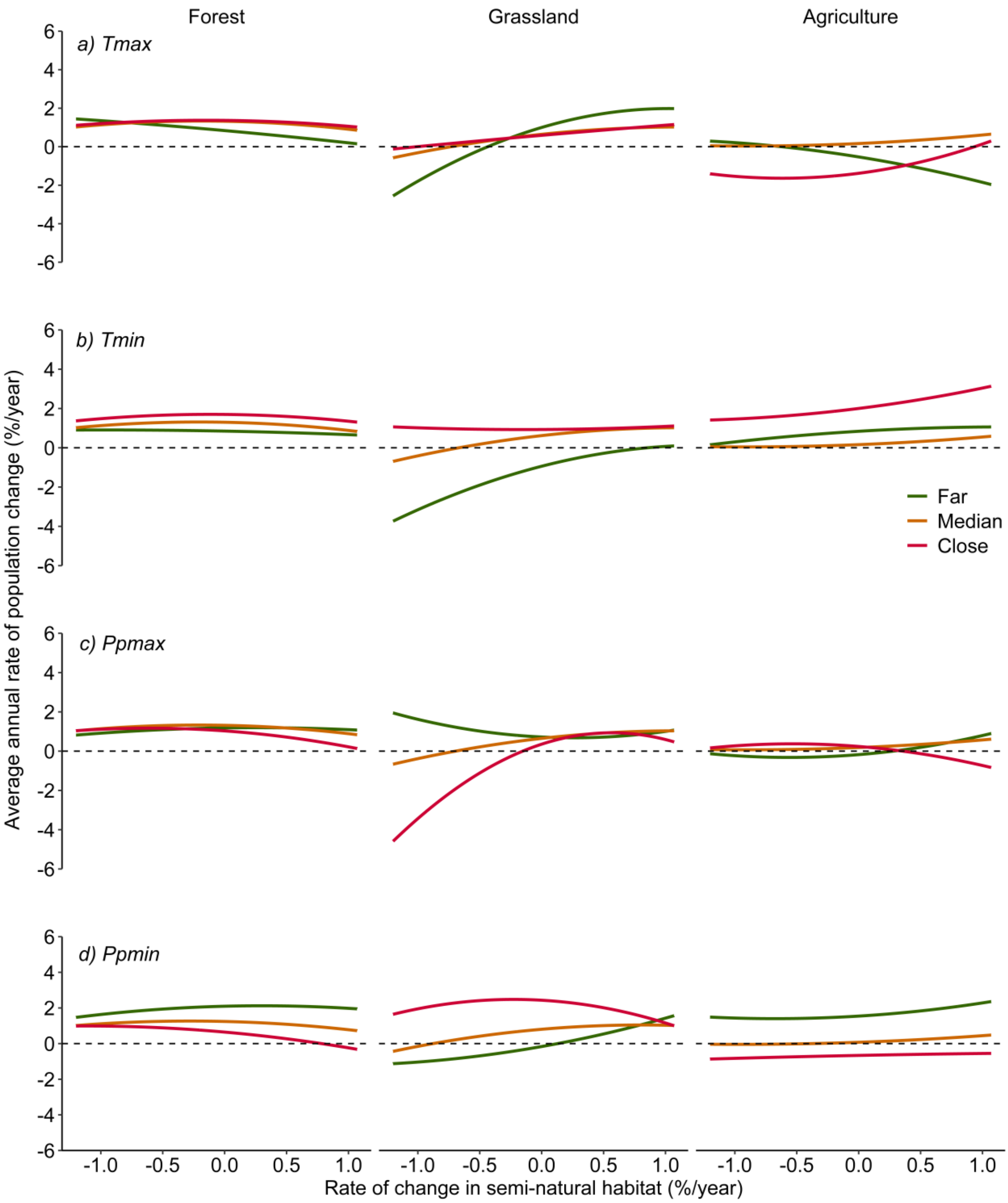

Figure S2: The average annual rate of population change across different starting land-use types (forest, grassland, agriculture), depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to (a) maximum temperature of the warmest month (T_{max}), (b) minimum temperature of the coldest month (T_{min}), (c) precipitation of the wettest month (Pp_{max}) or (d) precipitation of the driest month (Pp_{min}). For (a) and (c) far, median, and close, refer to the 10^{th}, 50^{th} and 90^{th} percentiles of T_{max} (0.73, 0.82, 0.91) and Pp_{max} (0.09, 0.20, 0.56) positions, respectively, in the dataset. For (b) and (d), far, median, and close refer to the 90^{th}, 50^{th} and 10^{th} percentiles of T_{min} (0.44, 0.32, 0.19) and Pp_{min} (0.08, 0.03, 0) positions, respectively, in the dataset. The x-axis is truncated at the 10^{th} and 90^{th} percentile of the rates of sampled values.

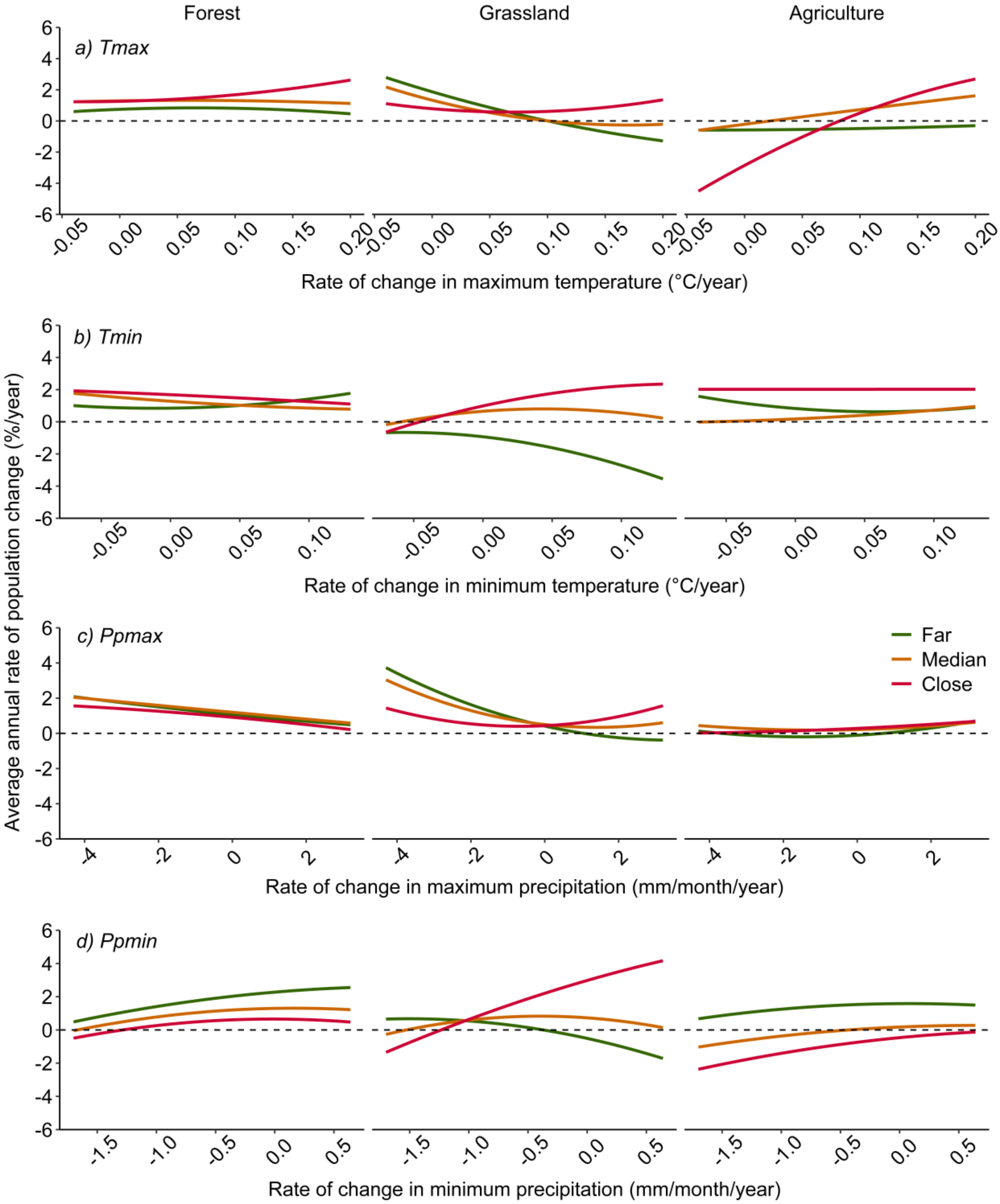

Figure S3: The average annual rate of population change across different starting land-use types (forest, grassland, agriculture), depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were (a) maximum temperature of the warmest month (T_{max}), (b) minimum temperature of the coldest month (T_{min}), (c) precipitation of the wettest month (Pp_{max}), and (d) precipitation of the driest month (Pp_{min}). For (a) and (c) far, median, and close, refer to the 10^{th}, 50^{th} and 90^{th} percentiles of T_{max} (0.73, 0.82, 0.91) and Pp_{max} (0.09, 0.20, 0.56) positions, respectively, in the dataset. For (b) and (d), far, median, and close refer to the 90th, 50th and 10th percentiles of T_{min} (0.44, 0.32, 0.19) and Pp_{min} (0.08, 0.03, 0) positions, respectively, in the dataset. The x-axis is truncated at the 10th and 90th percentile of the rates of sampled values.

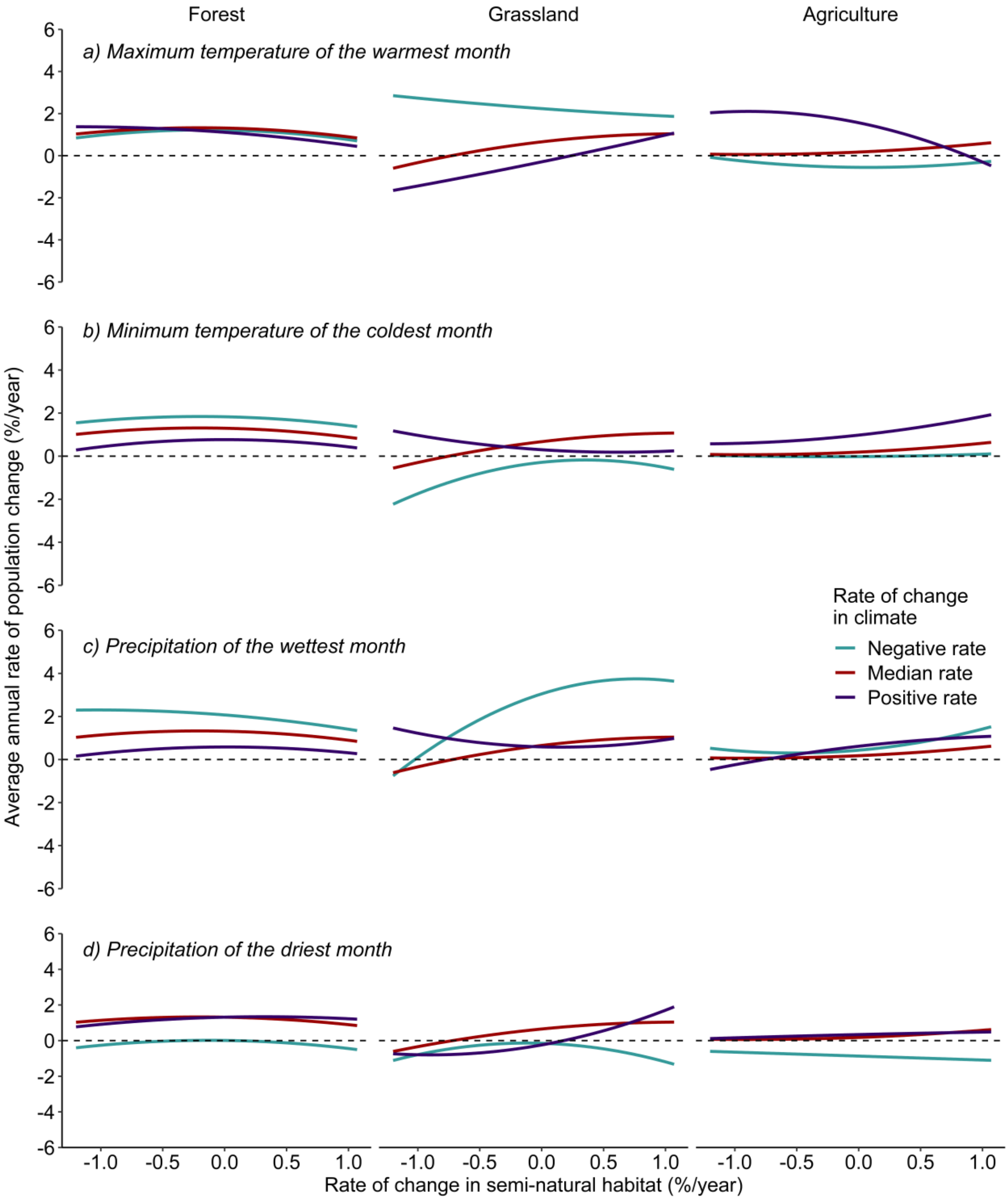

Figure S4: The average annual rate of population change across different starting land-use types (forest, grassland, agriculture), depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to (a) maximum temperature of the warmest month (°C/year), (b) minimum temperature of the coldest month (°C/year), (c) precipitation of the wettest month (monthly mm/year), and (d) precipitation of the driest month (monthly mm/year). Negative, median, and positive rates refer to the 10^{th}, 50^{th}, and 90^{th} percentiles of rate of change in each climatic variable, respectively (-0.04, 0.04, and 0.20 °C/year for maximum temperature of the warmest month; -0.08, 0, and 0.13 °C/year for minimum temperature of the coldest month; -4.33, -0.59, and 3.19 mm/year for precipitation of the wettest month; and -1.70, -0.26, and 0.64 mm/year for precipitation of the driest month). The x-axis is truncated at the 10^{th} and 90^{th} percentile of the rates of sampled values.

Appendix 4: Comparing climatic position measures

To check the robustness of our climatic position measure, we also calculated starting climatic position using the average maximum and minimum temperature and precipitation conditions (CRU Time-series data v. 4.03; Harris & Jones, 2020[WJ3]) in the three years up to and including the first year of a population's time-series (instead of just using data from the first year, as described in the main text). We then ran a model (using the same structure as described in the main text) using this climatic position measure. The model had a higher AIC (ΔAIC = 25.9) compared to the final model reported in the main text, but the overall results (figs. S5-6) were very similar.

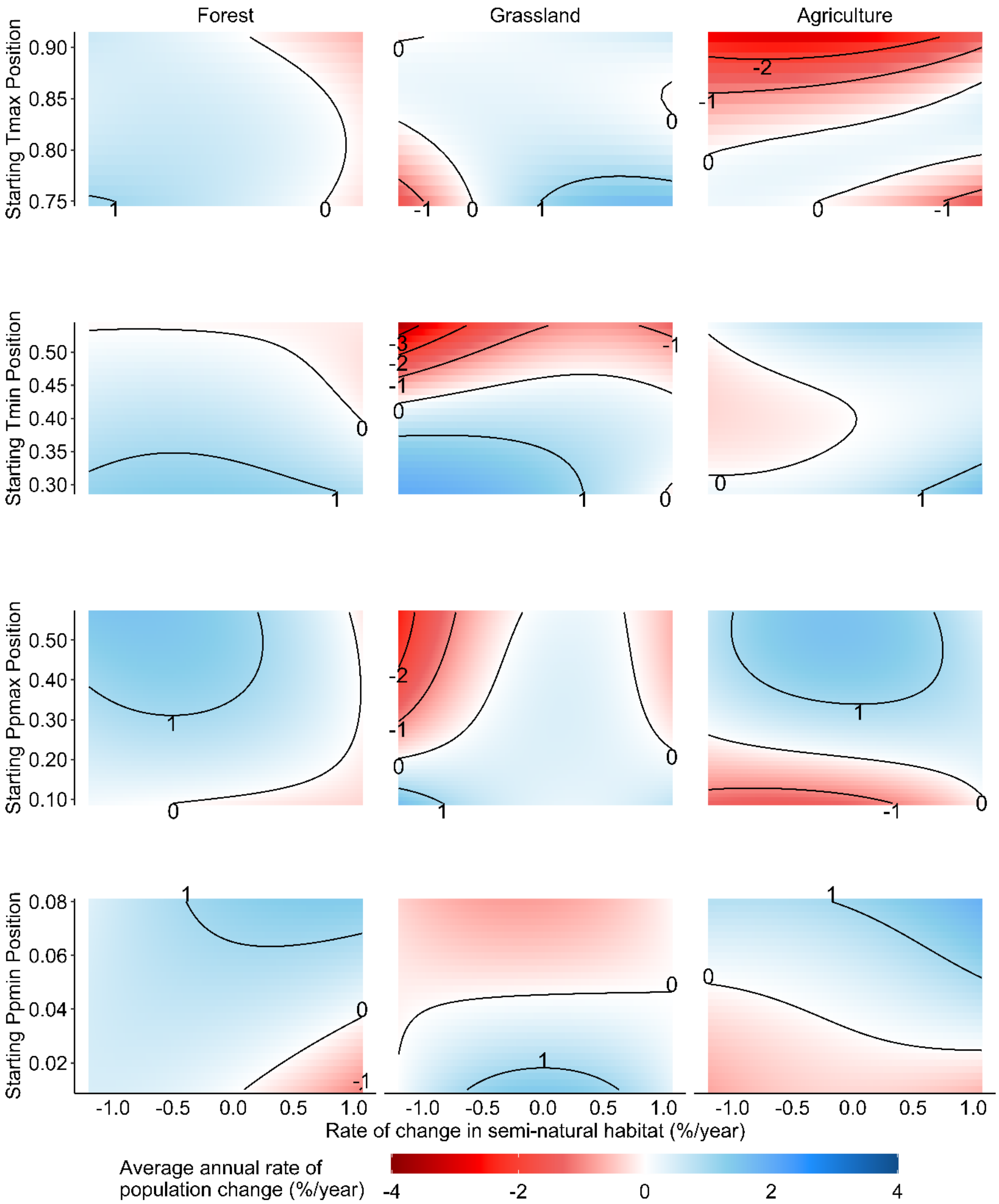

Figure S5: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position (calculated using the average maximum and minimum temperature and precipitation conditions in the three years up to and including the first year of a population's time-series) with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month

(Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

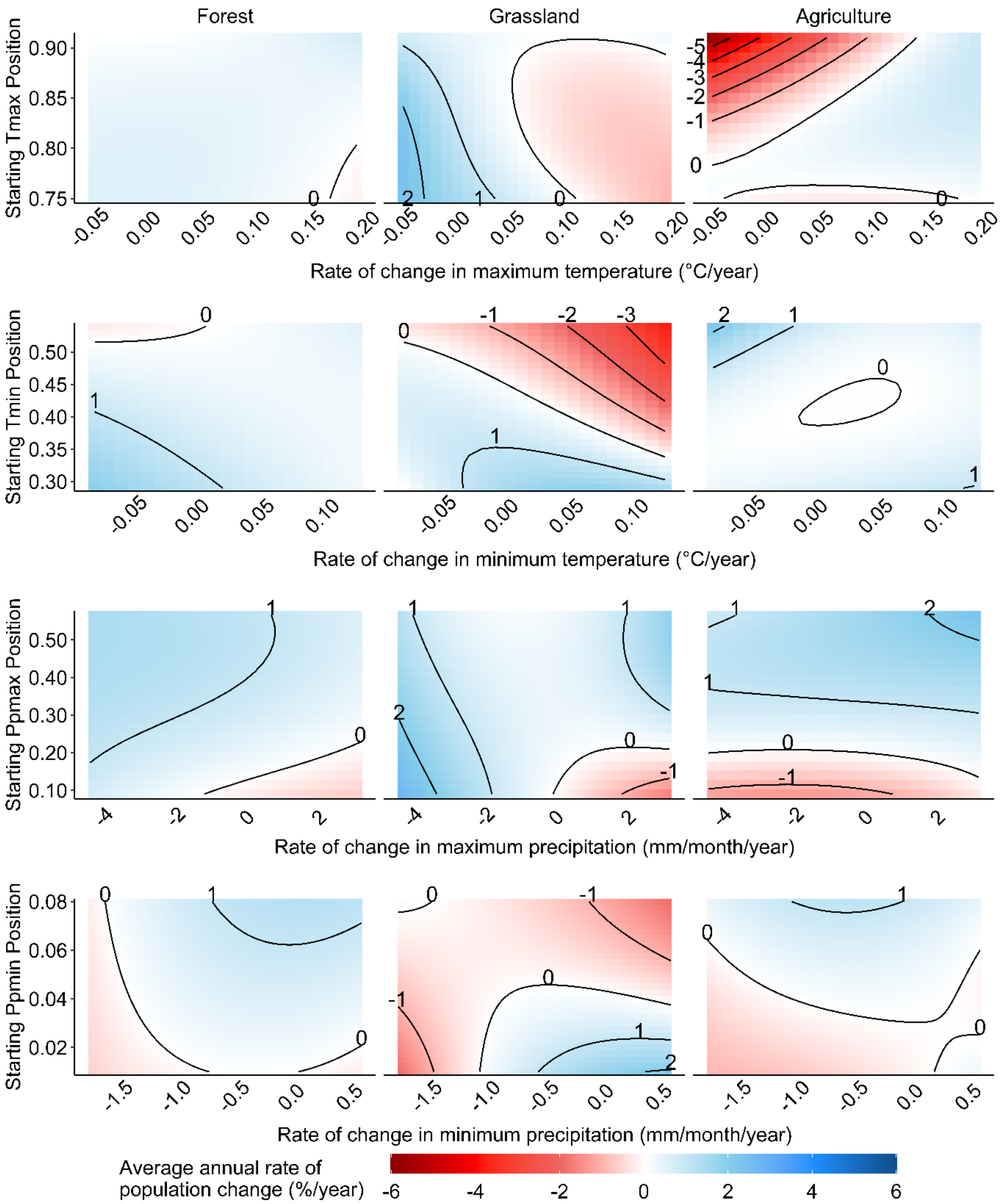

Figure S6: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position (calculated using the average maximum and minimum temperature and precipitation conditions in the three years up to and including the first year of a population's time-series). Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Further, to check the robustness of our estimates of climatic limits, as well as calculating species' climatic limits as described in the main text, we also (1) used the CRU Time-series data v. 4.03 (Harris & Jones, 2020), extracting climatic data from 1992, to calculate species' climatic limits (rather than using WorldClim data), (2) used occurrence records from the Global Biodiversity Information Facility (GBIF[WJ4]; GBIF 2015, https://www.gbif.org) to estimate climatic limits (rather than the species distribution maps), and (3) used the CRU Time-series data along with the GBIF occurrence records to estimate climatic limits. From GBIF, we extracted occurrence records for each species in our final dataset (324 species were also found in GBIF) and, for each species, used the highest maximum temperature of the warmest month, lowest minimum temperature of the coldest month, highest precipitation of the wettest month and lowest precipitation of the driest month from (a) WorldClim version 1.4 (Hijmans, Cameron, Parra, Jones, & Jarvis 2005) and (b) CRU Time-series data v. 4.03 (Harris & Jones, 2020), extracting climatic data from 1992, from the across these locations to define the species' thermal and precipitation tolerance limits. Following this, for the populations in our final dataset, climatic positions were calculated in the same way as described in the main text, but using the species' estimated realised climatic tolerance limits found using the three methods above. The correlations between the starting climatic positions estimated using the different methods are presented below (table S7).

Table S7: Correlations (Pearson's correlation coefficient, *r*), between populations' starting climatic positions estimated by using species' distribution maps (described in the main text; BirdLife International 2012; IUCN 2016a-b, 2017a-c, 2018a-b, 2019a-c[WJ5]) and WorldClim climate maps (Hijmans et al., 2005) and (1) using species' distribution maps and climate data from the CRU Time-series data (Harris & Jones, 2020), or (2) using occurrence data from the Global Biodiversity Information Facility (GBIF 2015) and WorldClim climate maps, or (3) using occurrence data from GBIF (GBIF 2015) and CRU Time-series climate data (Harris & Jones, 2020). Climatic positions were produced for four climatic variables: maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), and precipitation of the wettest (Pp_{max}) and driest (Pp_{min}) months (see main text).

Climatic position	Estimated using IUCN or BirdLife International distribution maps and CRU climate data	Estimated using GBIF occurrence data and WorldClim climate maps	Estimated using GBIF occurrence data and CRU climate data
Tmax	0.93	0.87	0.83
Tmin	0.93	0.78	0.79
Ppmax	0.90	0.88	0.79
Ppmin	0.93	0.90	0.85

We also reran our final model three more times, replacing the climatic position measures with those calculated by (1) using CRU Time-series data (instead of WorldClim data) and species distribution maps, (2) using GBIF data (instead of species' distribution maps) and WorldClim climate data and (3) using CRU Time-series data and GBIF data, to estimate climatic limits. Results of the model run using the climatic positions calculated using climatic limits derived from CRU Time-series data and species' distribution maps (figs. S7-8) were very similar to the results presented in the main text (but the model had a higher AIC, ΔAIC = 19.6). The patterns of results using climatic positions derived from GBIF data along with WorldClim data or CRU Time-series data were on the whole very similar to the results reported in the main text (figs. S9-[WJ6]12). As mentioned in the main text, the key differences included that, unlike the final model, negative rates of population change were observed for populations (a) in agriculture where thermal extremes had got warmer and the population had originally experienced extreme temperatures close to their hot thermal limit (high starting T_{max} position) or further from their cold thermal limit (high starting T_{min} position; fig. S10, S12) and (b) in grasslands where populations rapidly lost surrounding SNH and had low starting T_{min} positions or low starting Pp_{max} positions (fig. S9, S11). Further, when GBIF data were used alongside WorldClim data to estimate climatic limits, other differences included (a) the negative rates of change observed above for populations in agriculture with lower starting Pp_{min} positions under different rates of change in SNH and minimum precipitation (figs. 4-5) were not observed (instead the rate of change varied around 0% – 1% per year; figs. S9-10) and (b) the negative rates of change observed above for populations starting in grasslands with high Pp_{max} positions and experiencing low negative rates of change in SNH (fig. 4) were dampened to less negative rates of population change (between -1% and 0% per year; fig. S9).

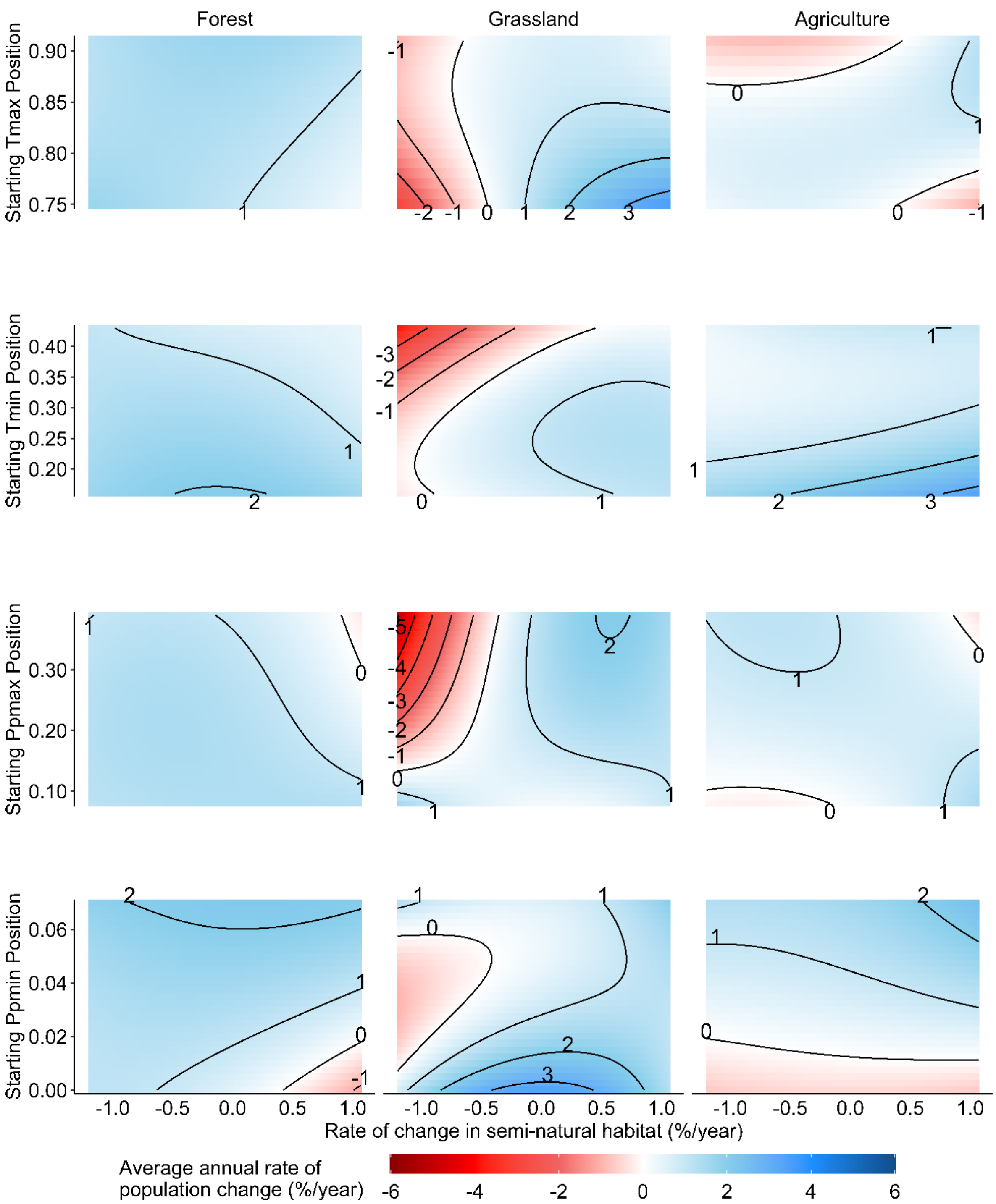

Figure S[WJ7]7: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position (calculated using species' distribution maps and CRU Time-series data, extracting climatic data from 1992, to estimate species' climatic limits) with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

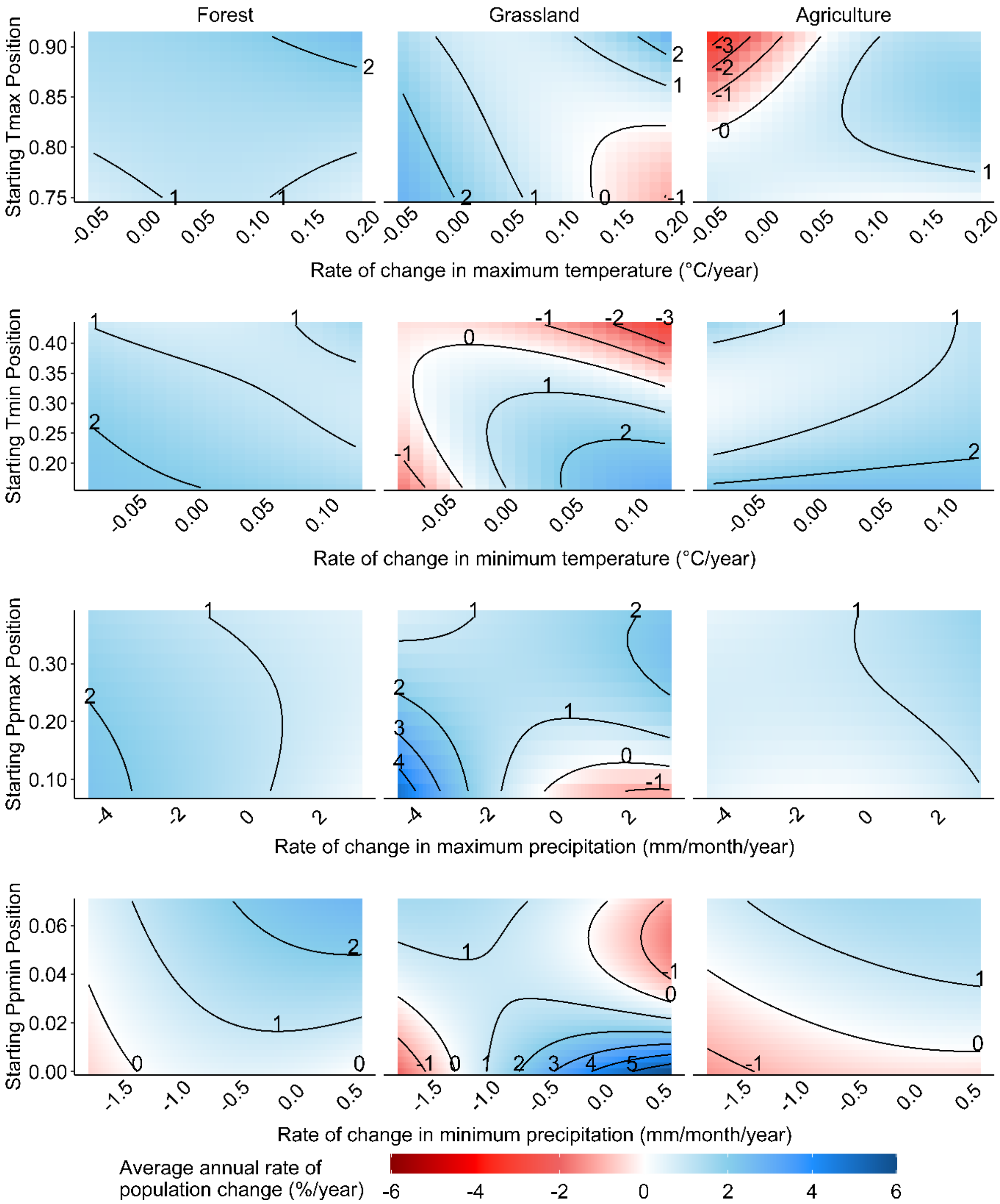

Figure S8: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position (calculated using species distribution maps and CRU Time-series data, extracting climatic data from 1992, to estimate species' climatic limits). Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

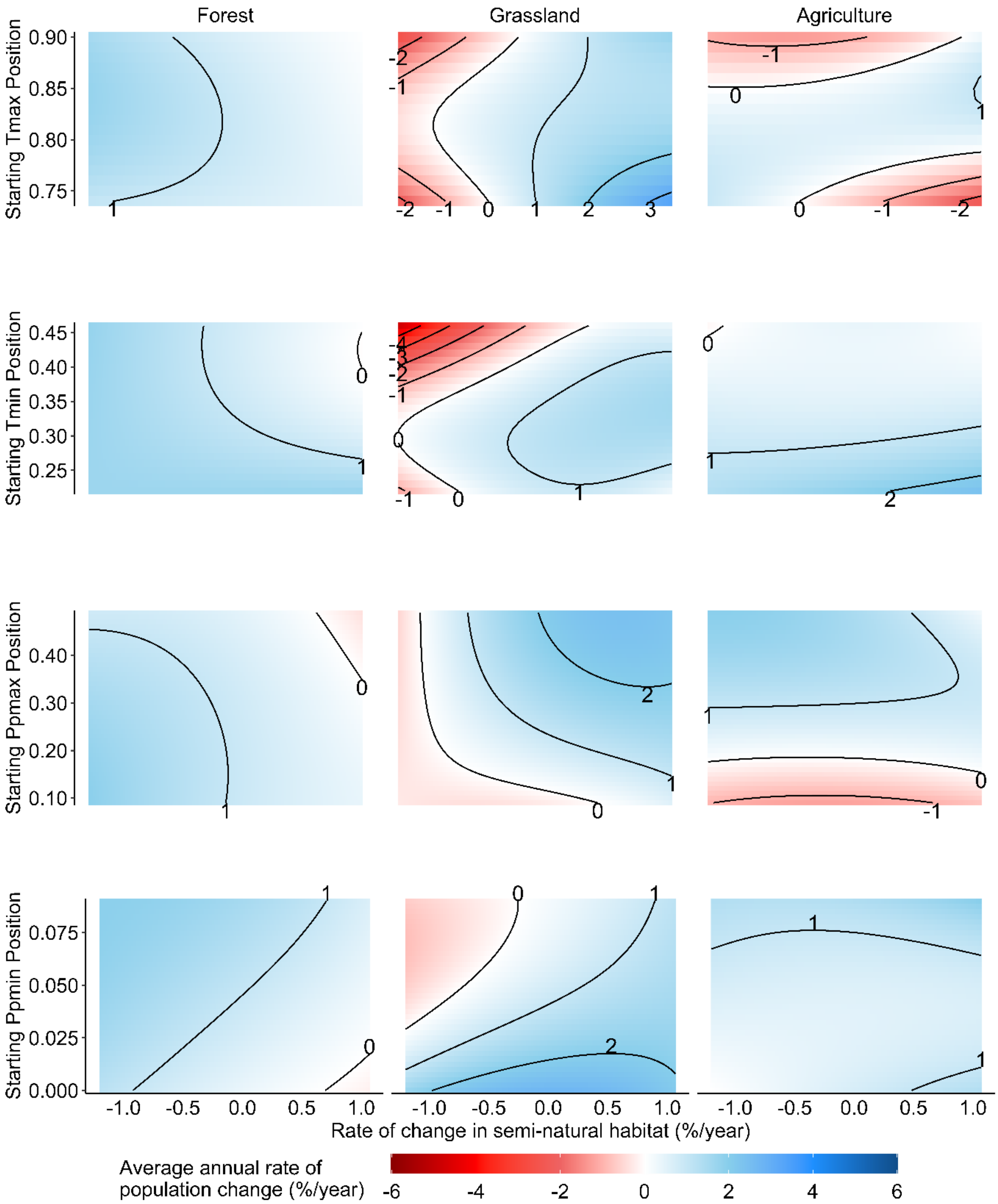

Figure S9: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position (calculated using WorldClim data and GBIF occurrence data to estimate species' climatic limits) with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

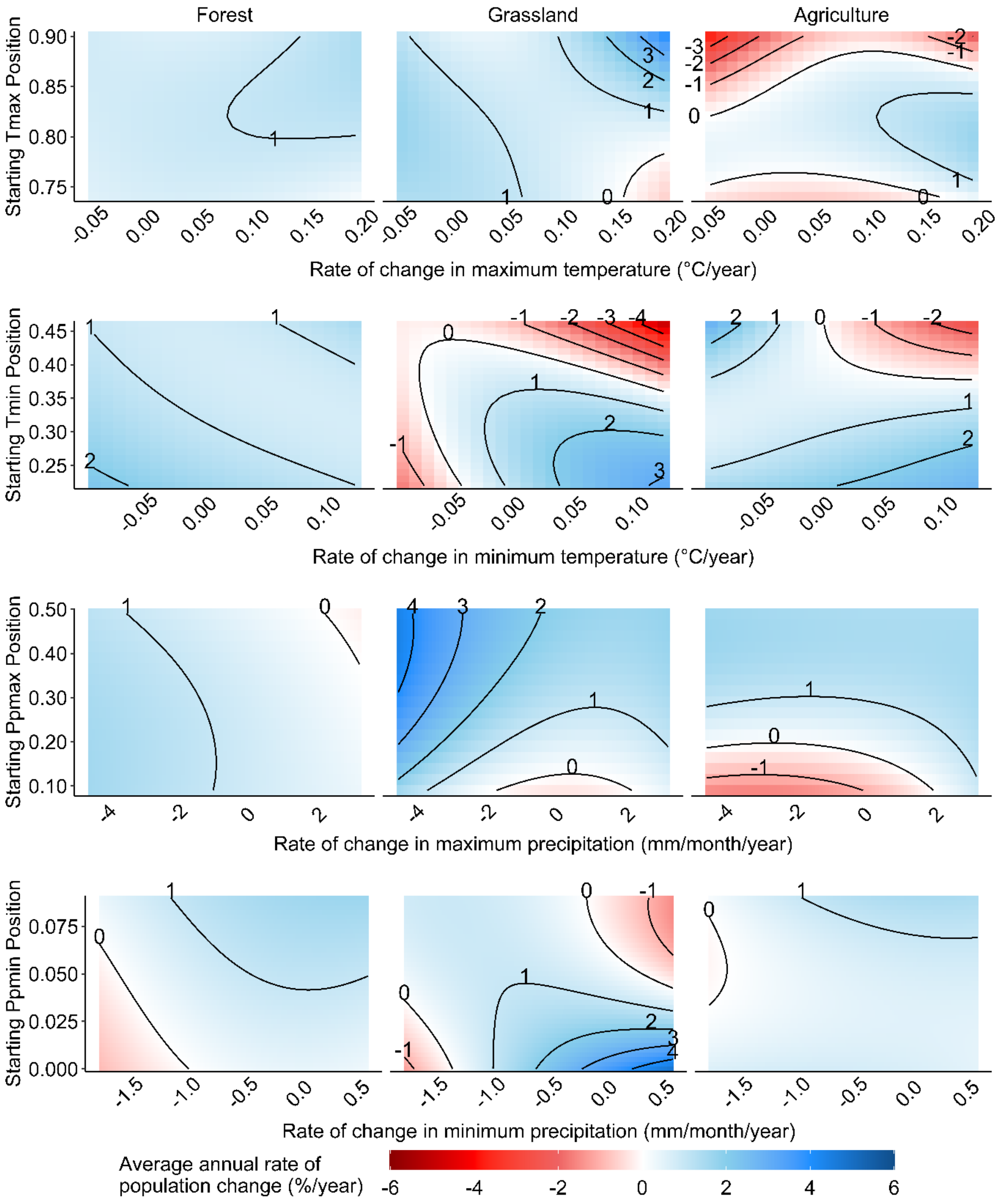

Figure S10: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position (calculated using WorldClim data and GBIF occurrence data to estimate species' climatic limits). Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

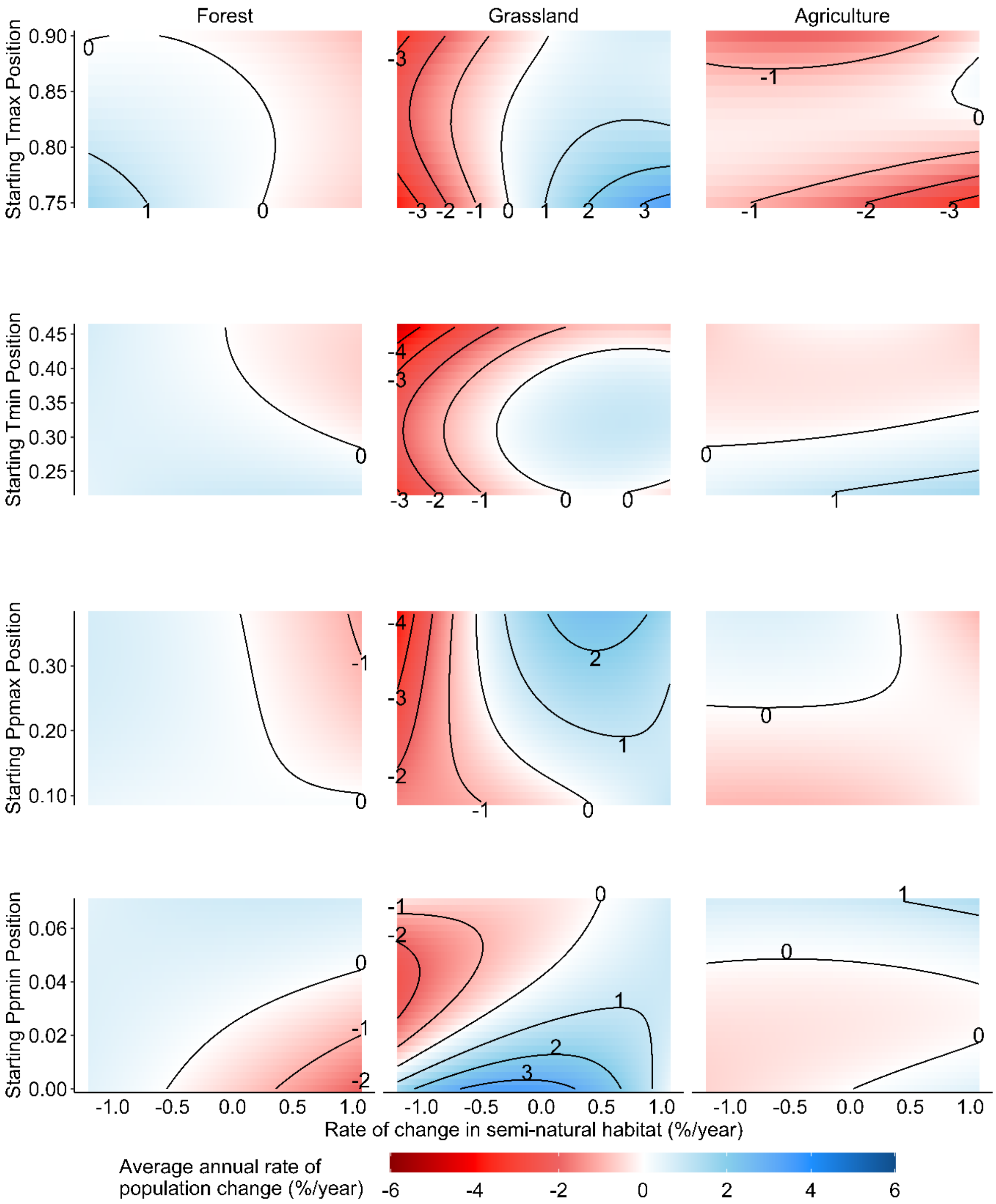

Figure S[WJ8]11: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position (calculated using GBIF occurrence data and CRU Time-series data, extracting climatic data from 1992, to estimate species' climatic limits) with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

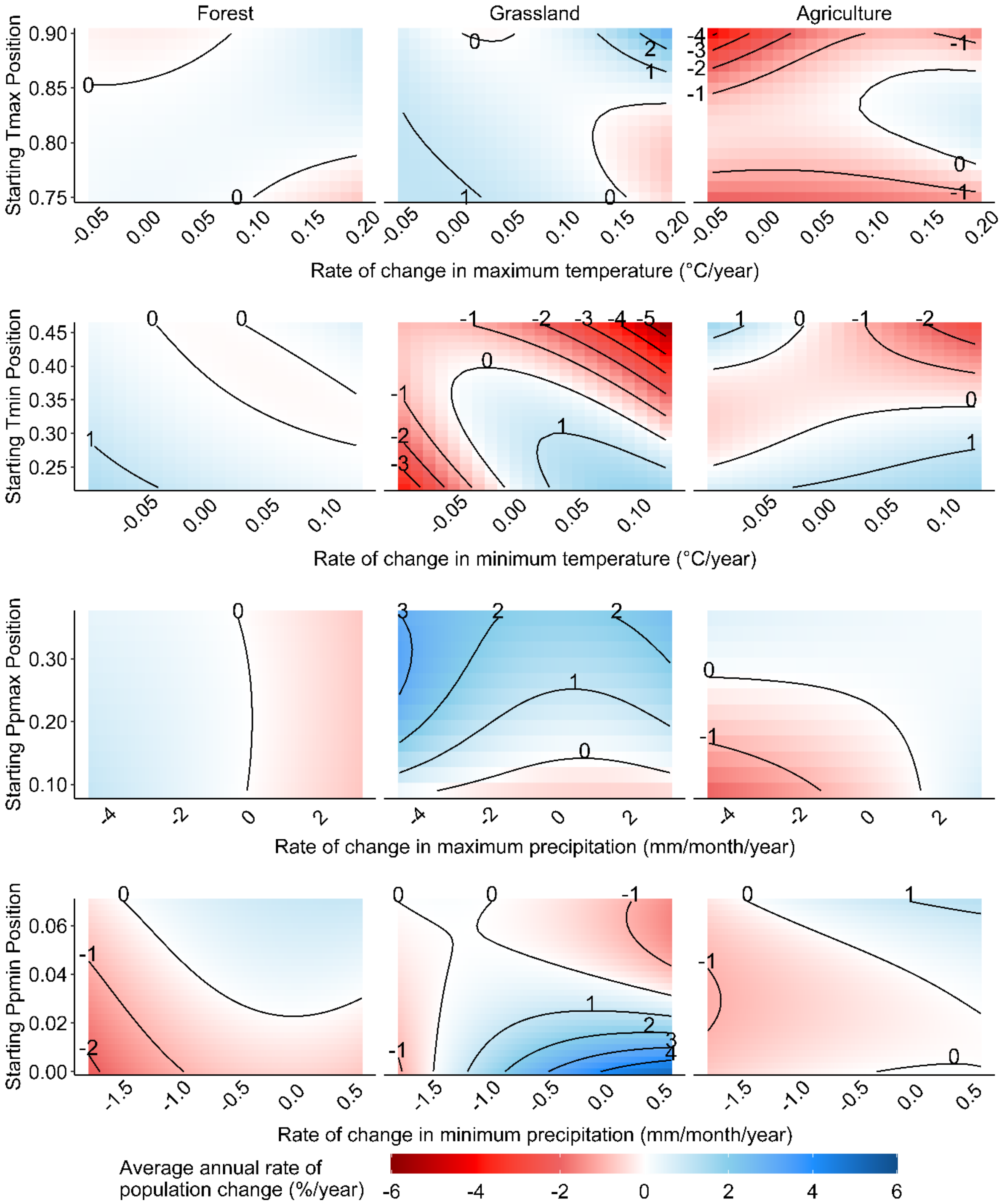

Figure S12: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position (calculated using GBIF occurrence data and CRU Time-series data, extracting climatic data from 1992, to estimate species' climatic limits). Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 5: Models including starting percentage of semi-natural habitat

As a sensitivity test, we ran the final model reported within the main text, but included the percentage of semi-natural habitat (SNH) within a 1-km radius in the first year a population was measured, instead of starting land-use type, in the model. The percentage of surrounding SNH was added into the model as a continuous linear fixed effect, and included in all the same interactions as was starting land-use type in the final model in the main text. This model had a higher AIC than the final model in the main text, and also had a lower marginal R^2 value. The results are presented below (figs. S13-16).

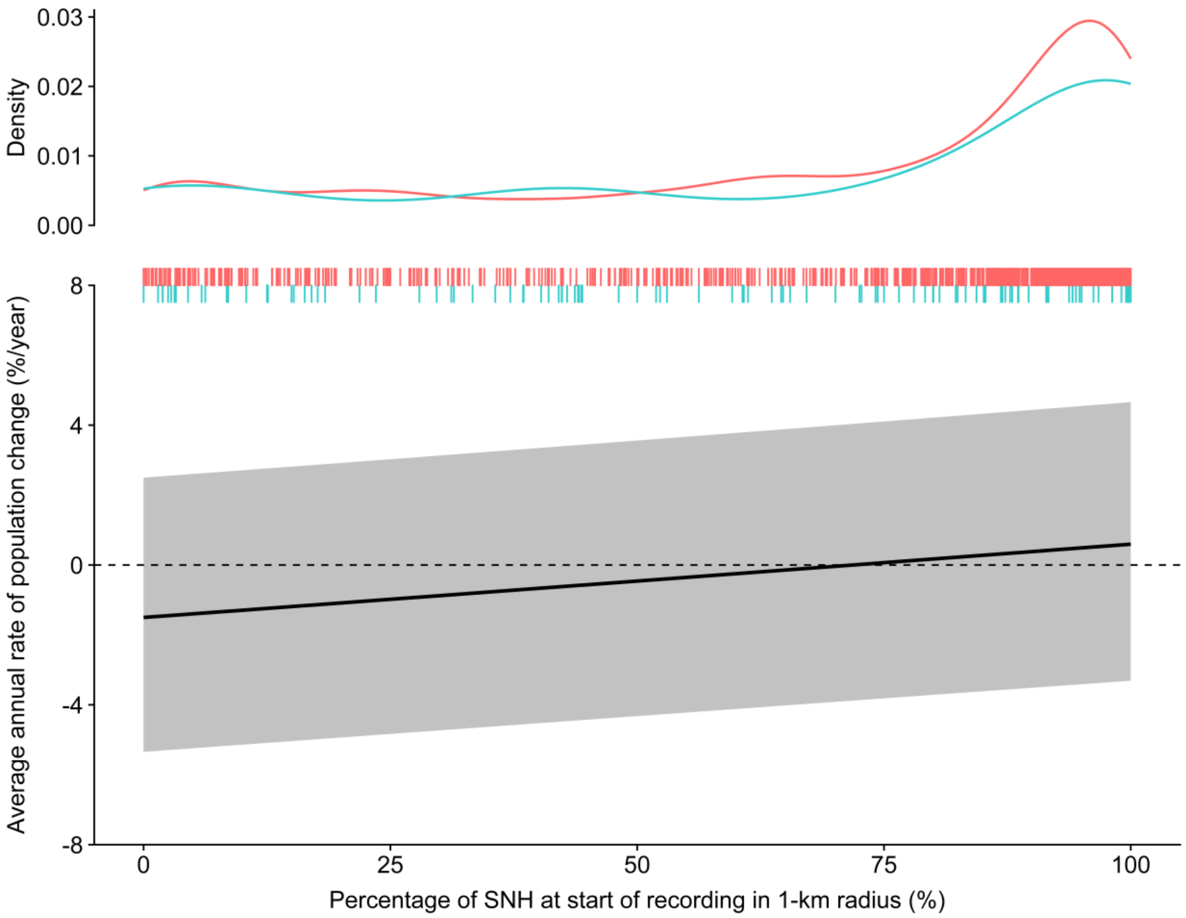

Figure S13: The average annual rate of population change depending on the percentage of semi-natural habitat (SNH) within a 1-km radius of the population in the first year they were measured. Error margins denote ±1 standard error. The density and rug plots at the top of the figure show the distribution of populations from the Living Planet database (blue) and BioTIME database (red).

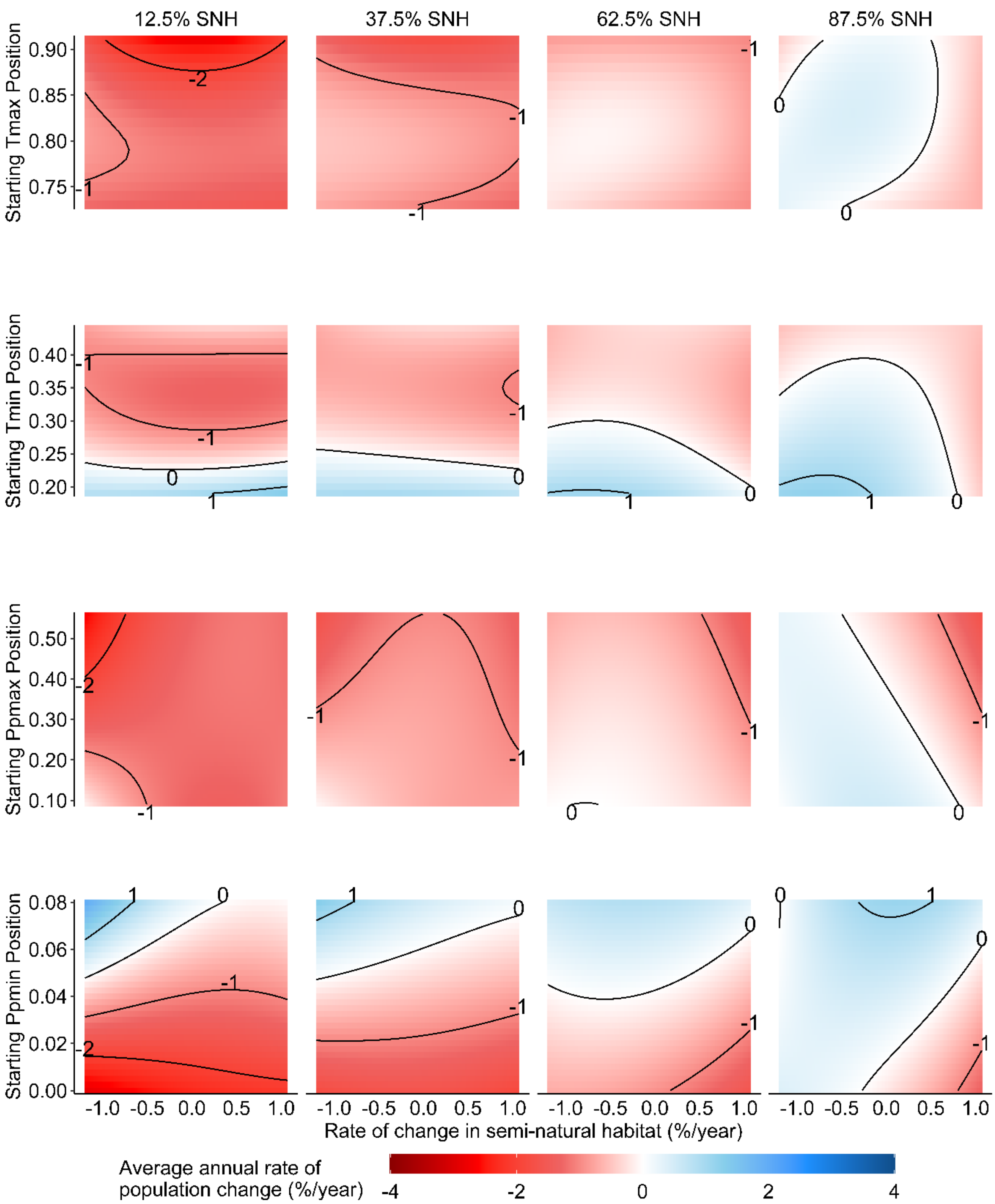

Figure S14: The average annual rate of population change for populations starting in areas with different percentages of semi-natural habitat (SNH) in the surrounding 1-km radius (rather than starting land-use type), [WJ9][WJ10]depending on: (i) the average annual rate of change in semi-natural habitat; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10[th] and 90[th] percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

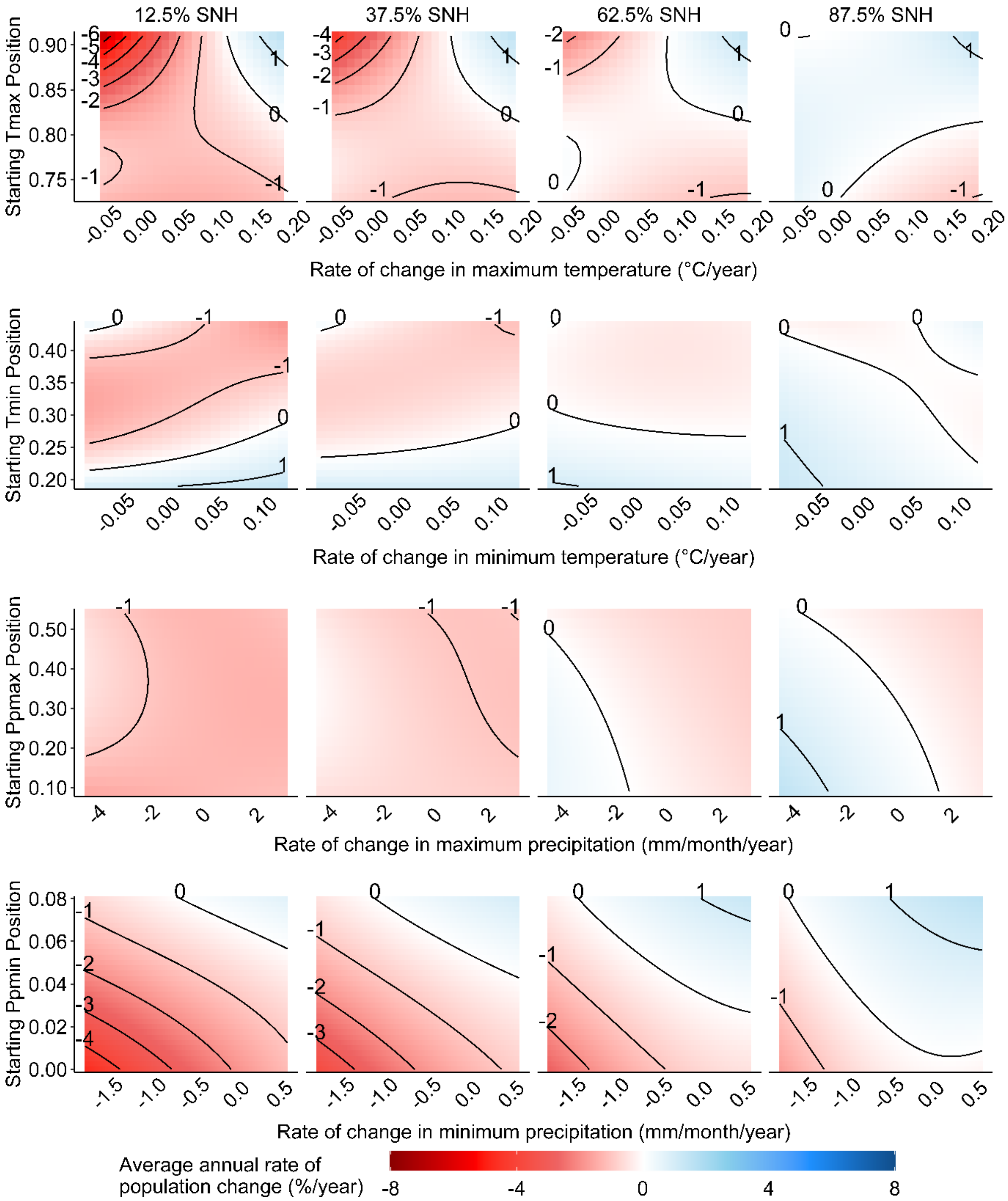

Figure S15: The average annual rate of population change for populations starting in areas with different percentages of semi-natural habitat (SNH) in the surrounding 1-km radius (rather than starting land-use type), depending on: (i) the average annual rate of change in climate; and (ii) a population’s starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

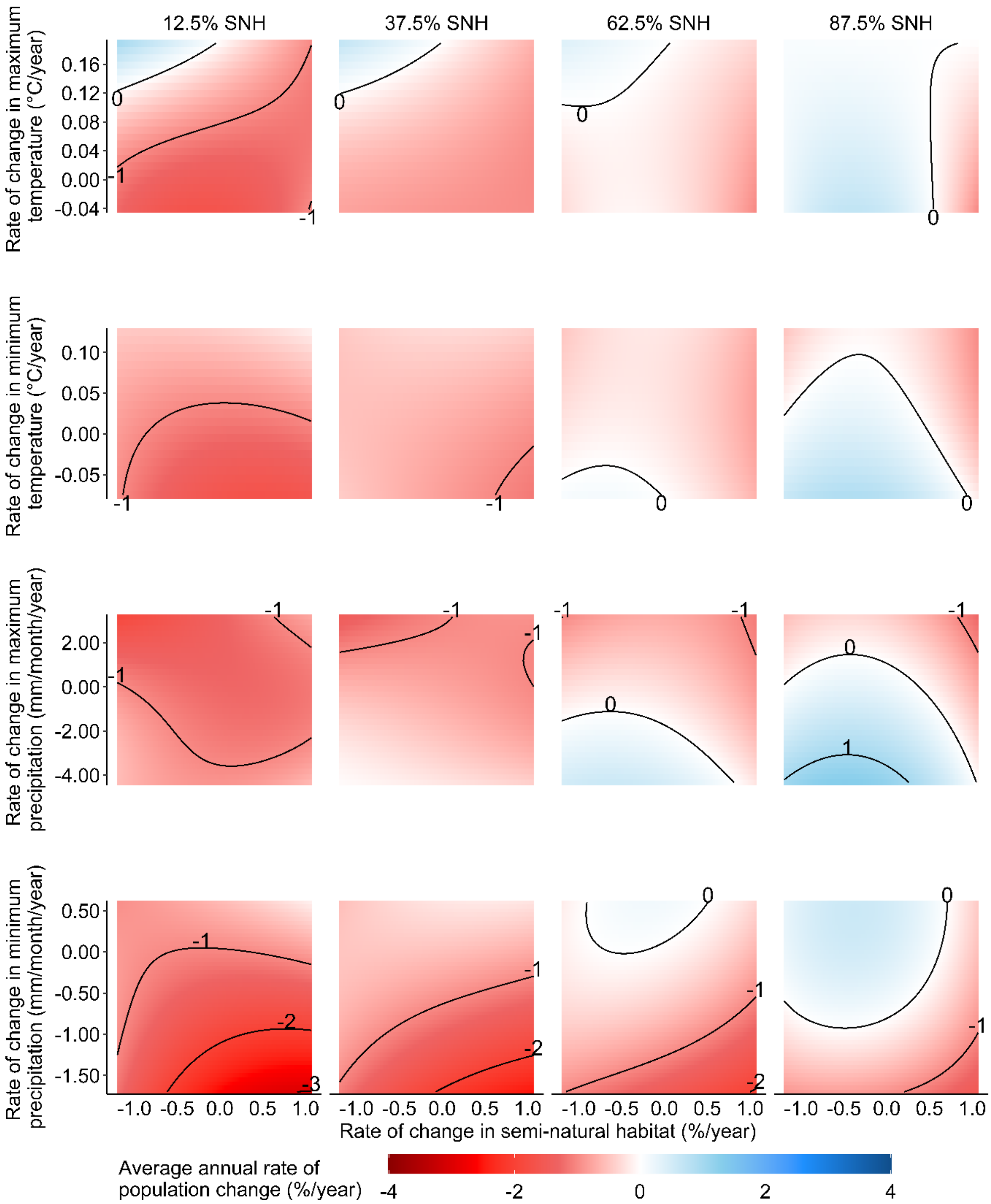

Figure S16: The average annual rate of population change for populations starting in areas with different percentages of semi-natural habitat (SNH) in the surrounding 1-km radius (rather than starting land-use type), depending on: (i) the average annual rate of change in semi-natural habitat; and (ii) rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 6: Comparison between land cover datasets

To check the consistency of land-use types across data sources, we downloaded a global map of terrestrial habitat types for the year 2015 (Jung et al., 2020a, 2020b)[WJ11] and compared it to the 2015 land cover map from the European Space Agency Climate Change Initiative (ESA CCI; ESA Land Cover CCI project team, Defourny, 2019) used in our analysis. For each unique site (n = 1,151) within our dataset, whether there was a population estimate for a population there in the year 2015 or not, we extracted the site's land-use type from both the 2015 ESA land cover map (using the same broader categories of agriculture, forest, grassland, wetland, urban, and other, as for the starting land-use types in the main text) and Jung et al.'s (2020a) terrestrial habitat map. We grouped Jung et al.'s (2020a) habitat types into broader categories (grouping A) based on their IUCN habitat classification scheme, and further into a smaller number of categories (grouping B) to match those groups used for starting land-use types in our analysis (although wetland and urban populations were removed from the final model due to small sample sizes; table S8). Then, for each location, we compared the extracted land uses. In particular, we wanted to ensure that there were not a large number of plantations or pastures at sites that we classed as forest or grasslands, respectively, as land-cover maps may miss these land uses.

For 71% of locations, the land-use type extracted from the ESA land cover map matched that from Jung et al.'s (2020a) terrestrial habitat map. For the other sites the land uses differed, and we detail these differences in table S9.

Table S8: The land-use type groupings used for the global map of terrestrial habitat types (Jung et al., 2020a). Grouping A groups the habitats into broader categories and grouping B further groups the habitats to match those used for starting land-use types in our analysis.

IUCN habitat classification scheme used by Jung et al. (2020a)	Grouping A	Grouping B
1. Forest	Forest	Forest
1.1. Forest – Boreal		
1.2. Forest - Subarctic		
1.3. Forest – Subantarctic		
1.4. Forest – Temperate		
1.5. Forest – Subtropical/tropical dry		
1.6. Forest – Subtropical/tropical moist lowland		
1.7. Forest – Subtropical/tropical mangrove vegetation above high tide level		
1.8. Forest – Subtropical/tropical swamp		
1.9. Forest – Subtropical/tropical moist montane		
2. Savanna	Savanna	Grassland
2.1. Savanna - Dry		
2.2. Savanna - Moist		
3. Shrubland	Shrubland	Other
3.1. Shrubland – Subarctic		
3.2. Shrubland – Subantarctic		
3.3. Shrubland – Boreal		
3.4. Shrubland –Temperate		

3.5. Shrubland – Subtropical/tropical dry		
3.6. Shrubland – Subtropical/tropical moist		
3.7. Shrubland – Subtropical/tropical high altitude		
3.8. Shrubland – Mediterranean-type shrubby vegetation		
4. Grassland	Grassland	Grassland
4.1. Grassland – Tundra		
4.2. Grassland – Subarctic		
4.3. Grassland – Subantarctic		
4.4. Grassland – Temperate		
4.5. Grassland – Subtropical/tropical dry		
4.6. Grassland – Subtropical/tropical seasonally wet/flooded		
4.7. Grassland – Subtropical/tropical high altitude		
5. Wetlands (inland)	Wetland	Wetland
5.1. Wetlands (inland) – Permanent rivers/streams/creeks (includes waterfalls)		
5.2. Wetlands (inland) – Seasonal/intermittent/irregular rivers/streams/creeks		
5.3. Wetlands (inland) – Shrub dominated wetlands		
5.4. Wetlands (inland) – Bogs, marshes, swamps, fens, peatlands		
5.5. Wetlands (inland) – Permanent freshwater lakes (over 8 ha)		
5.6. Wetlands (inland) – Seasonal/intermittent freshwater lakes (over 8 ha)		
5.7. Wetlands (inland) – Permanent freshwater marshes/pools (under 8 ha)		
5.8. Wetlands (inland) – Seasonal/intermittent freshwater marshes/pools (under 8 ha)		

5.9. Wetlands (inland) – Freshwater springs and oases		
5.10. Wetlands (inland) – Tundra wetlands (inc. pools and temporary waters from snowmelt)		
5.11. Wetlands (inland) – Alpine wetlands (inc. temporary waters from snowmelt)		
5.12. Wetlands (inland) – Geothermal wetlands		
5.13. Wetlands (inland) – Permanent inland deltas		
5.14. Wetlands (inland) – Permanent saline, brackish or alkaline lakes		
5.15. Wetlands (inland) – Seasonal/intermittent saline, brackish or alkaline lakes and flats		
5.16. Wetlands (inland) – Permanent saline, brackish or alkaline marshes/pools		
5.17. Wetlands (inland) – Seasonal/intermittent saline, brackish or alkaline marshes/pools		
5.18. Wetlands (inland) – Karst and other subterranean hydrological systems (inland)		
6. Rocky Areas (e.g., inland cliffs, mountain peaks)	Rocky areas	---
7. Caves & Subterranean Habitats (non-aquatic) 7.1. Caves and Subterranean Habitats (non-aquatic) – Caves 7.2. Caves and Subterranean Habitats (non-aquatic) – Other subterranean habitats	Caves and subterranean habitats	---
8. Desert 8.1. Desert – Hot 8.2. Desert – Temperate 8.3. Desert – Cold	Desert	Other
9. Marine Neritic 9.1. Marine Neritic – Pelagic 9.2. Marine Neritic – Subtidal rock and rocky reefs	Marine Neritic	Marine Neritic^{+}

9.3. Marine Neritic – Subtidal loose rock/pebble/gravel		
9.4. Marine Neritic – Subtidal sandy		
9.5. Marine Neritic – Subtidal sandy-mud		
9.6. Marine Neritic – Subtidal muddy		
9.7. Marine Neritic – Macroalgal/kelp		
9.8. Marine Neritic – Coral Reef		
9.8.1. Outer reef channel		
9.8.2. Back slope		
9.8.3. Foreslope (outer reef slope)		
9.8.4. Lagoon		
9.8.5. Inter-reef soft substrate		
9.8.6. Inter-reef rubble substrate		
9.9 Seagrass (Submerged)		
9.10 Estuaries		
10 Marine Oceanic 10.1 Epipelagic (0–200 m) 10.2 Mesopelagic (200–1,000 m) 10.3 Bathypelagic (1,000–4,000 m) 10.4 Abyssopelagic (4,000–6,000 m) 11 Marine Deep Ocean Floor (Benthic and Demersal) 11.1 Continental Slope/Bathyl Zone (200–4,000 m)	Marine Oceanic	---

11.1.1 Hard Substrate		
11.1.2 Soft Substrate		
11.2 Abyssal Plain (4,000–6,000 m)		
11.3 Abyssal Mountain/Hills (4,000–6,000 m)		
11.4 Hadal/Deep Sea Trench (>6,000 m)		
11.5 Seamount		
11.6 Deep Sea Vents (Rifts/Seeps)		
12 Marine Intertidal	Marine Intertidal	---
12.1 Rocky Shoreline		
12.2 Sandy Shoreline and/or Beaches, Sand Bars, Spits, etc.		
12.3 Shingle and/or Pebble Shoreline and/or Beaches		
12.4 Mud Shoreline and Intertidal Mud Flats		
12.5 Salt Marshes (Emergent Grasses)		
12.6 Tidepools		
12.7 Mangrove Submerged Roots		
13 Marine Coastal/Supratidal	Marine Coastal	---
13.1 Sea Cliffs and Rocky Offshore Islands		
13.2 Coastal Caves/Karst		
13.3 Coastal Sand Dunes		
13.4 Coastal Brackish/Saline Lagoons/Marine Lakes		
13.5 Coastal Freshwater Lakes		

14 Artificial - Terrestrial	Artificial – terrestrial	---
14.1 Arable Land	Arable land	Agriculture
14.2 Pastureland	Pastureland	
14.3 Plantations	Plantations	
14.4 Rural Gardens	Rural gardens	Urban
14.5 Urban Areas	Urban areas	
14.6 Subtropical/Tropical Heavily Degraded Former Forest	Heavily degraded former forest	---
15 Artificial - Aquatic	Artificial – aquatic	---
15.1 Water Storage Areas [over 8 ha]		
15.2 Ponds [below 8 ha]		
15.3 Aquaculture Ponds		
15.4 Salt Exploitation Sites		
15.5 Excavations (open)		
15.6 Wastewater Treatment Areas		
15.7 Irrigated Land [includes irrigation channels]	Artificial – irrigated land and flooded agricultural land	---
15.8 Seasonally Flooded Agricultural Land		
15.9 Canals and Drainage Channels, Ditches	Artificial – aquatic	---
15.10 Karst and Other Subterranean Hydrological Systems [human-made]		
15.11 Marine Anthropogenic Structures		

15.12 Mariculture Cages		
15.13 Mari/Brackish-culture Ponds		
16 Introduced Vegetation	Introduced vegetation	---
17 Other	Other	---
18 Unknown	Unknown	---

--- denotes that no locations were within this land-use type, so it was not put into a grouping.

+ Sites in Marine Neritic land-use types were kept in their own grouping, not placed into one of those used in our main analysis.

Table S9: The number of sites from the final dataset in each land use under the 2015 ESA CCI land cover map and Jung et al.'s (2020a) terrestrial habitat map for 2015 (using Grouping A). The shaded grey boxes indicate agreement between the two maps (which included 71% of sites in the final dataset).

		ESA CCI land cover map					
		Forest	Grassland	Agriculture	Other	Urban	Wetland
Jung et al.'s (2020a) terrestrial habitat map (Grouping A)	Forest	633	20	40	27	1	0
	Grassland	14	22	22	26	0	1
	Savanna	7	1	9	7	0	0
	Arable land	4	6	100	1	0	0
	Pasturelands	7	6	10	2	1	0
	Plantation	24	4	3	1	0	0
	Shrubland	58	14	20	38	2	0
	Urban	0	3	4	0	6	0
	Rural gardens	0	0	2	0	0	0
	Wetland	1	0	1	0	0	0
	Marine neritic	2	0	1	0	0	0

Appendix 7: Rate of change in forest

As a sensitivity test, using the same structure of the final model reported in the main text, we ran another model that included average annual rate of change in the percentage of forest (instead of SNH) within a 1-km radius of the population. This model explained a very small amount more (0.086%) of the variation in rate of population change compared to the model presented in the main text, but overall patterns were similar (figs. S17-18). Although, for populations starting in grasslands, higher positive rates of population change were observed when rate of change in forest (rather than SNH) was included in the model. Further, we observe more negative rates of change for populations starting in agriculture with high T_{max} positions and experiencing rapid increases in surrounding forest (perhaps due to movement of individuals out of agriculture into these forested areas; fig. S17). The results for the three-way interactions that included rate of change in forest (starting land-use type × rate of change in forest × starting climatic position, and starting land-use type × rate of change in forest × rate of change in climate) are plotted below (figs. S17-18).

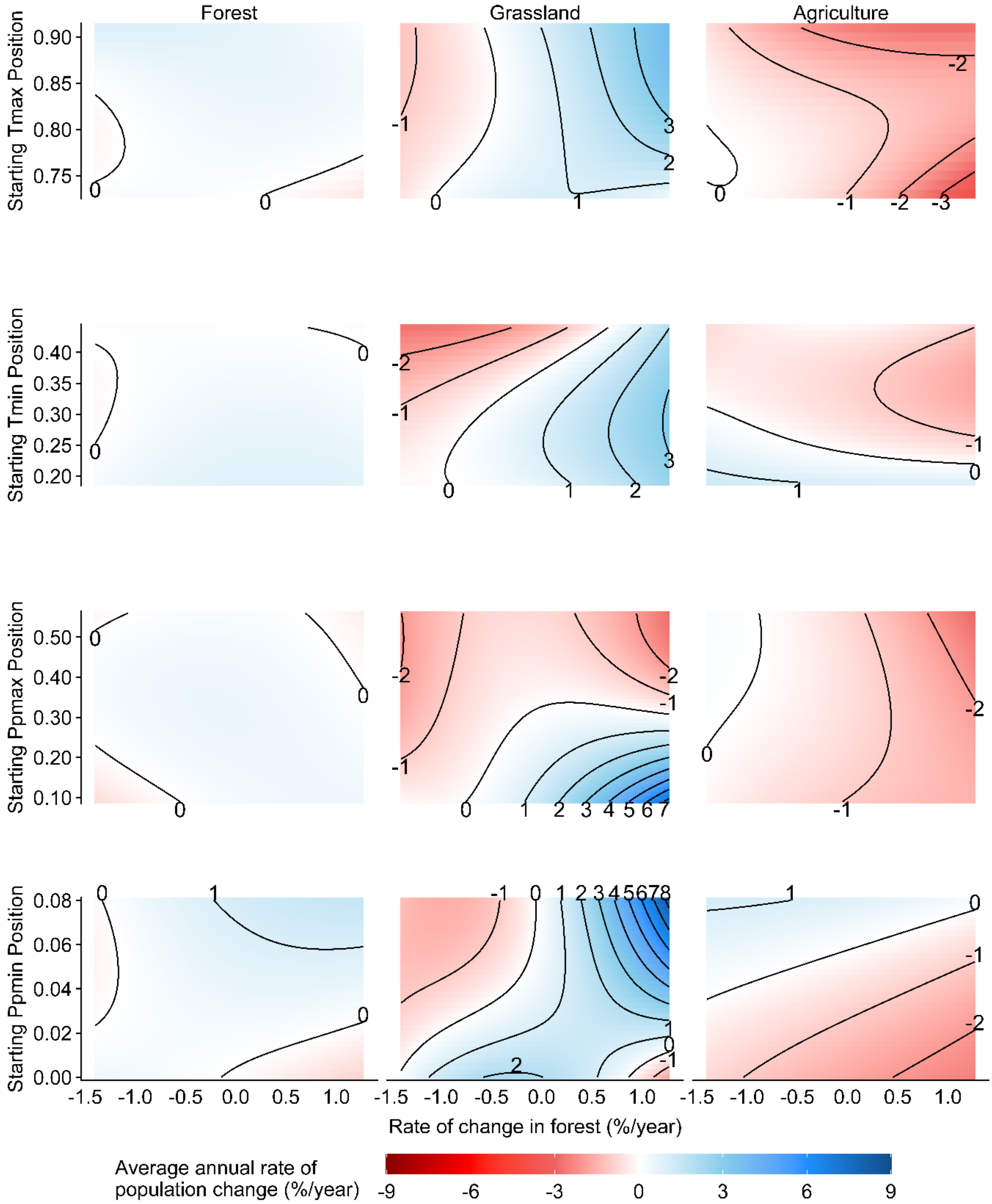

Figure S1[WJ12]7: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of forest (rather than semi-natural habitat) within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and

90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

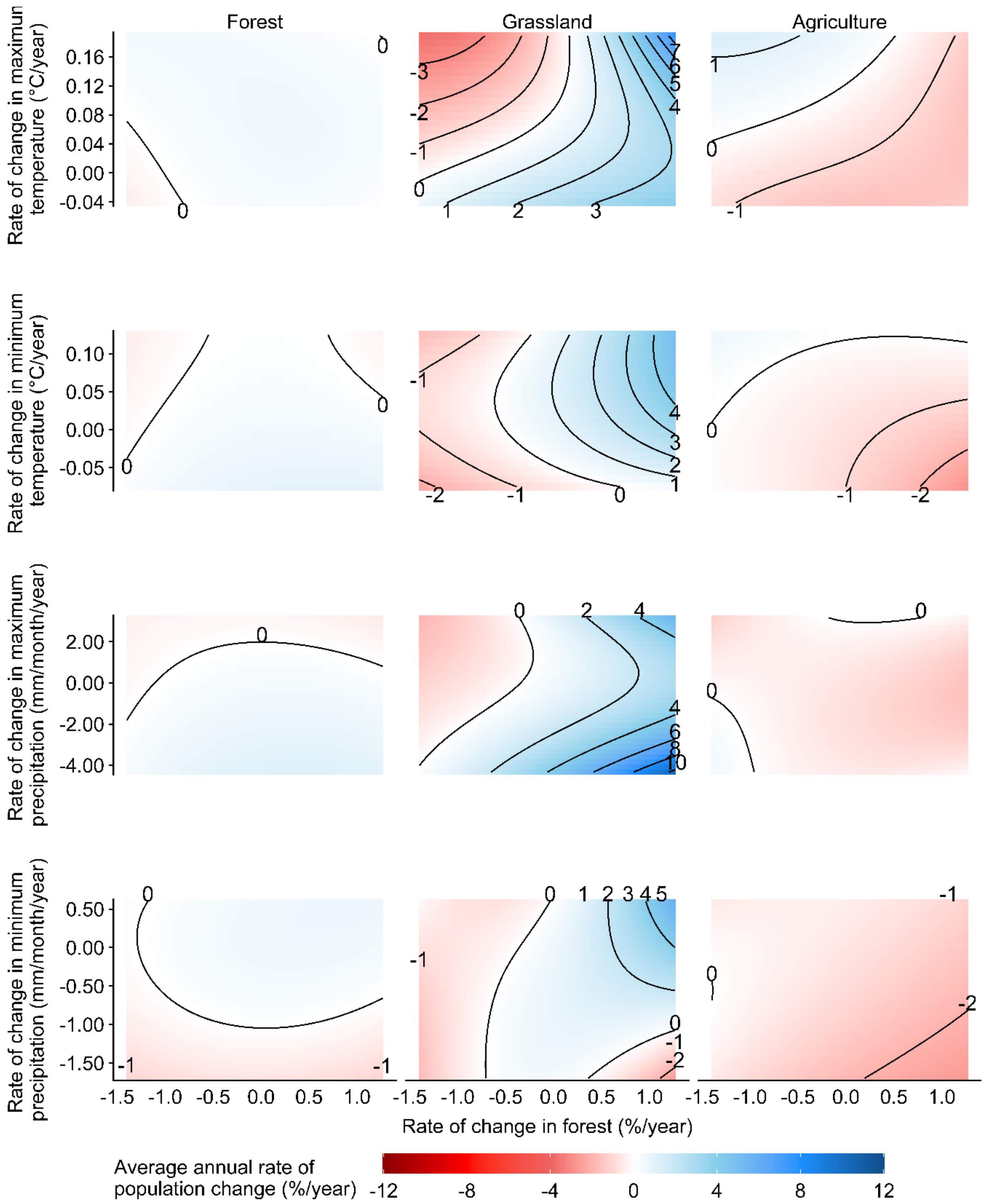

Figure S18: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of forest (rather than semi-natural habitat) within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. If comparing this plot to figure 6 in the main text, note the differences in scale for the average annual rate of population change[WJ13].

Appendix 8: Only including populations whose time-series had $R^2 \geq 0.5$ when fit to the GAM[WJ14]

We ran a model, using the same structure as the final model in the main text, but only including populations where the generalised additive model (GAM) fit to the population time-series with $R^2 \geq 0.5$, which left 1,639 populations (93 mammal, 1520 bird, 11 amphibian, and 15 reptile populations). In general, even though this model predicted more extreme annual rates of population change (in both the positive and negative direction), the overall patterns (figs. S19-21) were similar to that highlighted in the final model described in the main text. Nevertheless, there were a few differences in patterns observed for populations starting within grassland for a couple of the interactions (figs. S20-21), which may be due to the smaller number of populations starting in grassland included in this model (n = 201). In particular, the rapid declines of grassland populations with higher T_{min} or Pp_{max} positions that experienced fast declines in surrounding SNH were not observed when only populations whose time-series had $R^2 \geq 0.5$ were included in the model. Another difference between models was that, again for those populations starting in grassland, there were high positive rates of population change (as opposed to the negative rates of population change observed in the main text) for those populations with high T_{min} positions and experiencing faster increases in minimum temperature. The model including only populations whose time-series had $R^2 \geq 0.5$ also had a higher marginal R^2 than the final model reported in the main text, which may have been for a couple of reasons, including: (1[WJ15]) the time-series with greater variation in population measures over time have been removed, and (2) for some populations excluded from this model, larger variation in their population measures may be due to particular events (e.g., policy implementation, poisoning, or wild fires), that cannot be explained well by the variables in our model[WJ16].

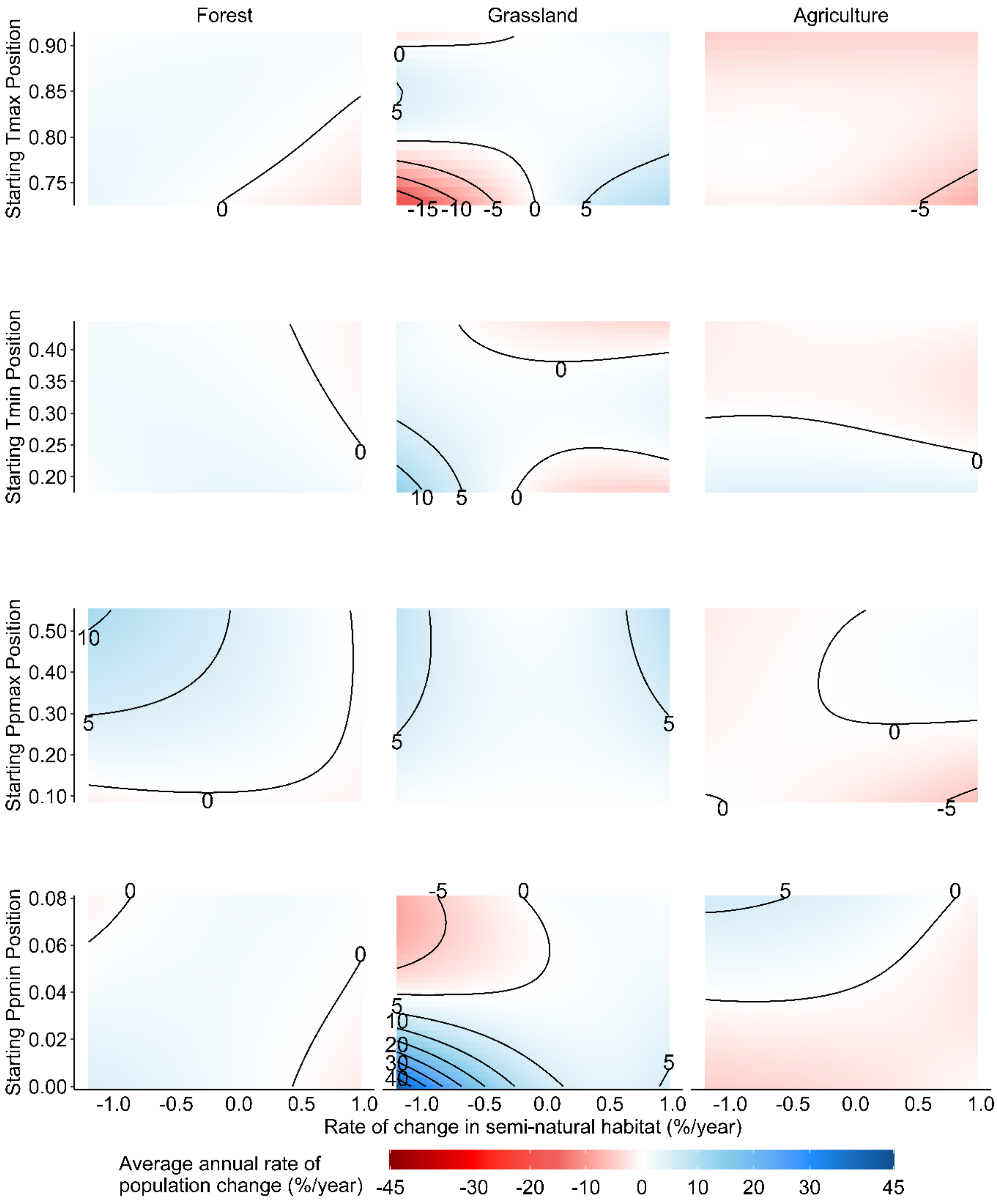

Figure S19: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). Only population time-series with $R^2 \geq 0.5$ when fitted to the GAM were included in this model. The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

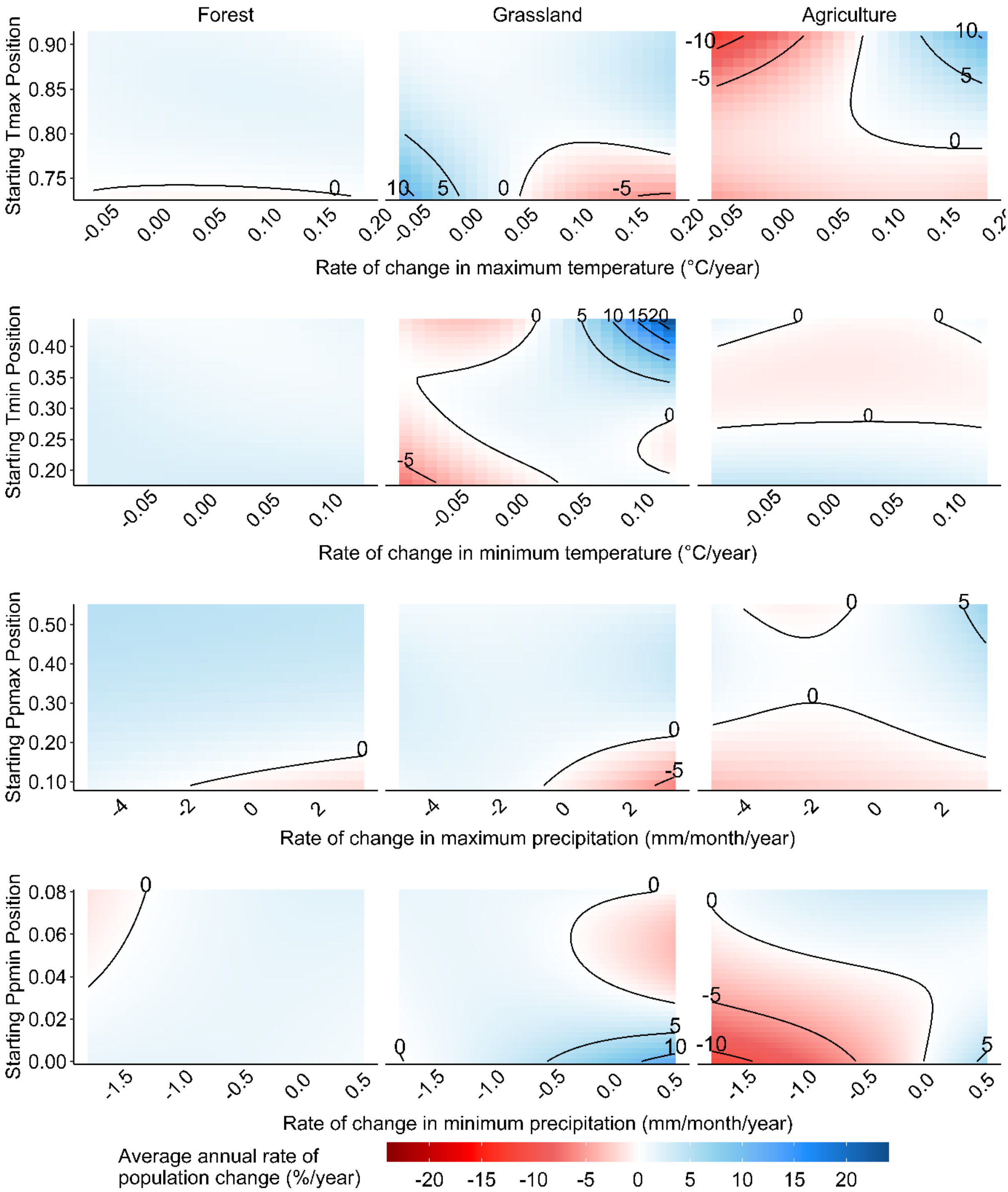

Figure S20: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). Only population time-series with $R^2 \geq 0.5$ when fitted to the GAM were included in this model. The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

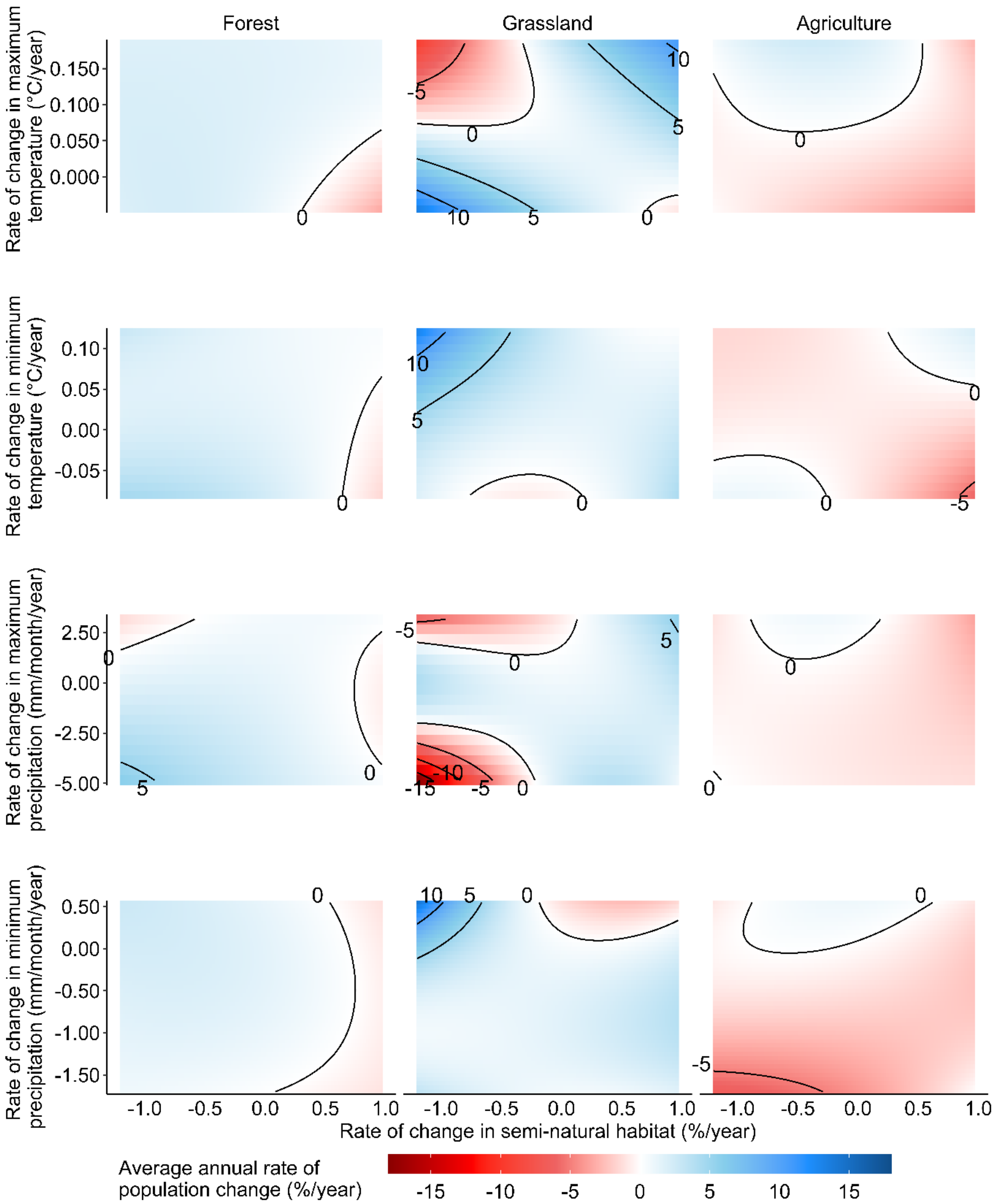

Figure S21: The average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). Only population time-series with $R^2 \geq 0.5$ when fitted to the GAM were included in this model. The x- and y-axes are truncated at the 10^{th} and 90^{th}

percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 9: Excluding extreme values

To ensure our results reported were not being influenced by extreme positive or negative rates of population change, we excluded time-series with $\overline{\boldsymbol{\lambda_Y}}$ above and below the upper and lower 97.5th and 2.5th percentile, respectively (which removed 358 populations; table S10), and ran the final model as described in the main text. This model explained slightly more variance (0.7%) than the final model reported in the main text, but overall patterns were similar. The results for the three focal three-way interactions are plotted below (figs. S22-24).

Table S10: Summary statistics for the population time-series analysed when populations with extreme rates of change (above and below the upper and lower 97.5th and 2.5th percentile, respectively) were removed from the final dataset. The table is split by the database the populations originated from (Living Planet database, [Living Planet Index database, January 2020], and the BioTIME database [Dornelas et al., 2018]). The average annual rate of change in semi-natural habitat refers to change within a 1-km radius surrounding each population. Fitted values were based on fixed effects only.

	Living Planet database	BioTIME database
Number of populations analysed	312	6453
Average annual rates of population change (% / year)		
Mean of observed (and fitted) values	-0.71 (0.08)	-0.06 (-0.38)
Median of observed (and fitted) values	-0.17 (-0.25)[WJ17]	0 (-0.39)
Number of populations with a positive (↑) or negative (↓) values	↑ 137 ↓ 175	↑ 3135 ↓ 3180
Mean length of population time-series (years)	13	15
Number of countries populations originated from	39	4
Average annual rates of change in semi-natural habitat		
Range (% / year)	-4.06[WJ18] – 3.97	-7.27 – 9.24
Mean (% / year)	-0.05	0.02
Median (% / year)	0	0.03
Number of populations with a positive (↑) or negative (↓) values	↑ 126 ↓ 139	↑ 3731 ↓ 2460
Percentage of populations starting in each starting land-use type (%, to 1 decimal place)		
Forest	62.8	54.5
Grassland	3.8	11.5
Agriculture	16.0	28.2
Other	17.3	5.8

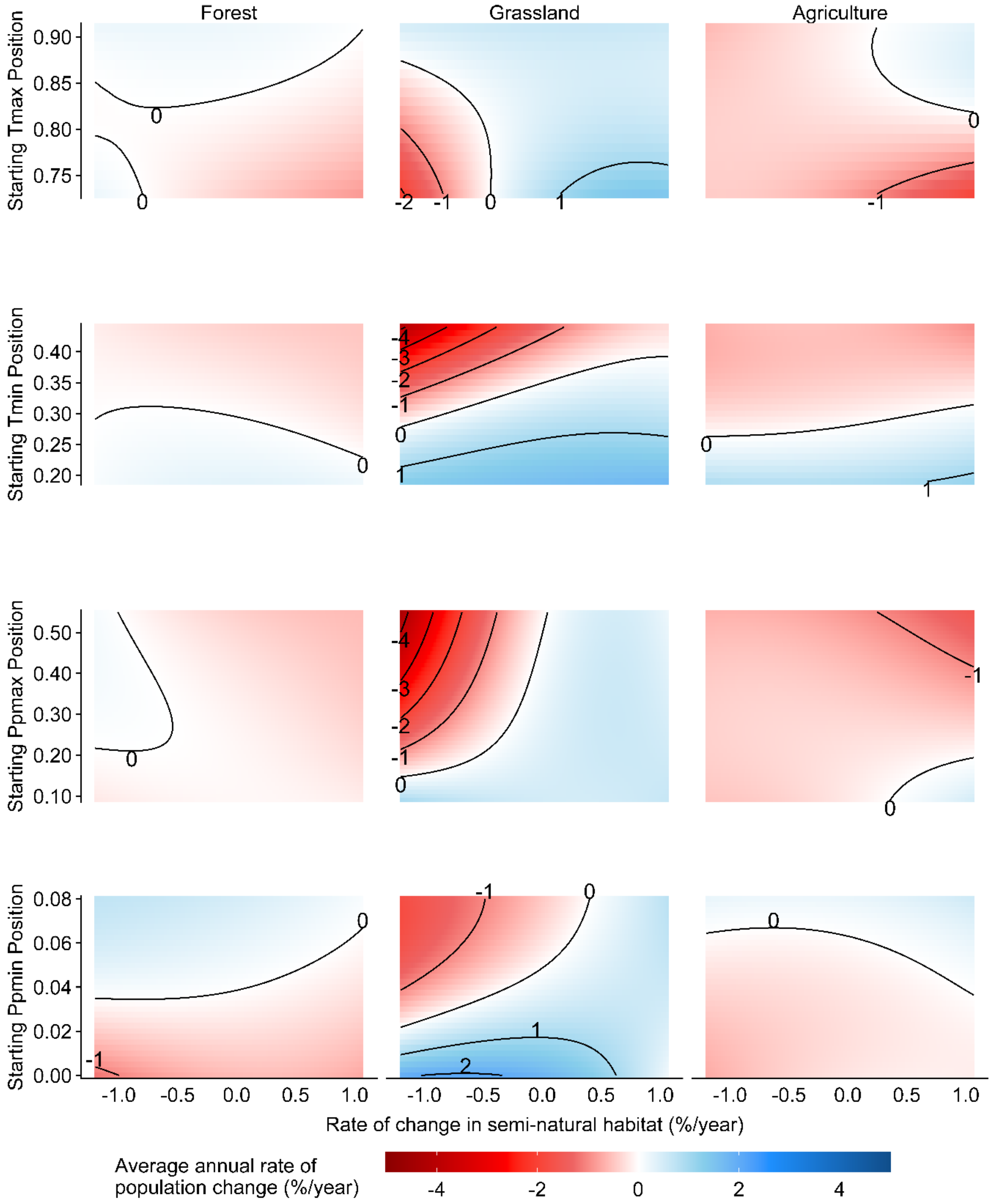

Figure S22: After excluding populations with extreme rates of population change (above and below the upper and lower 97.5th and 2.5th percentile, respectively), the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

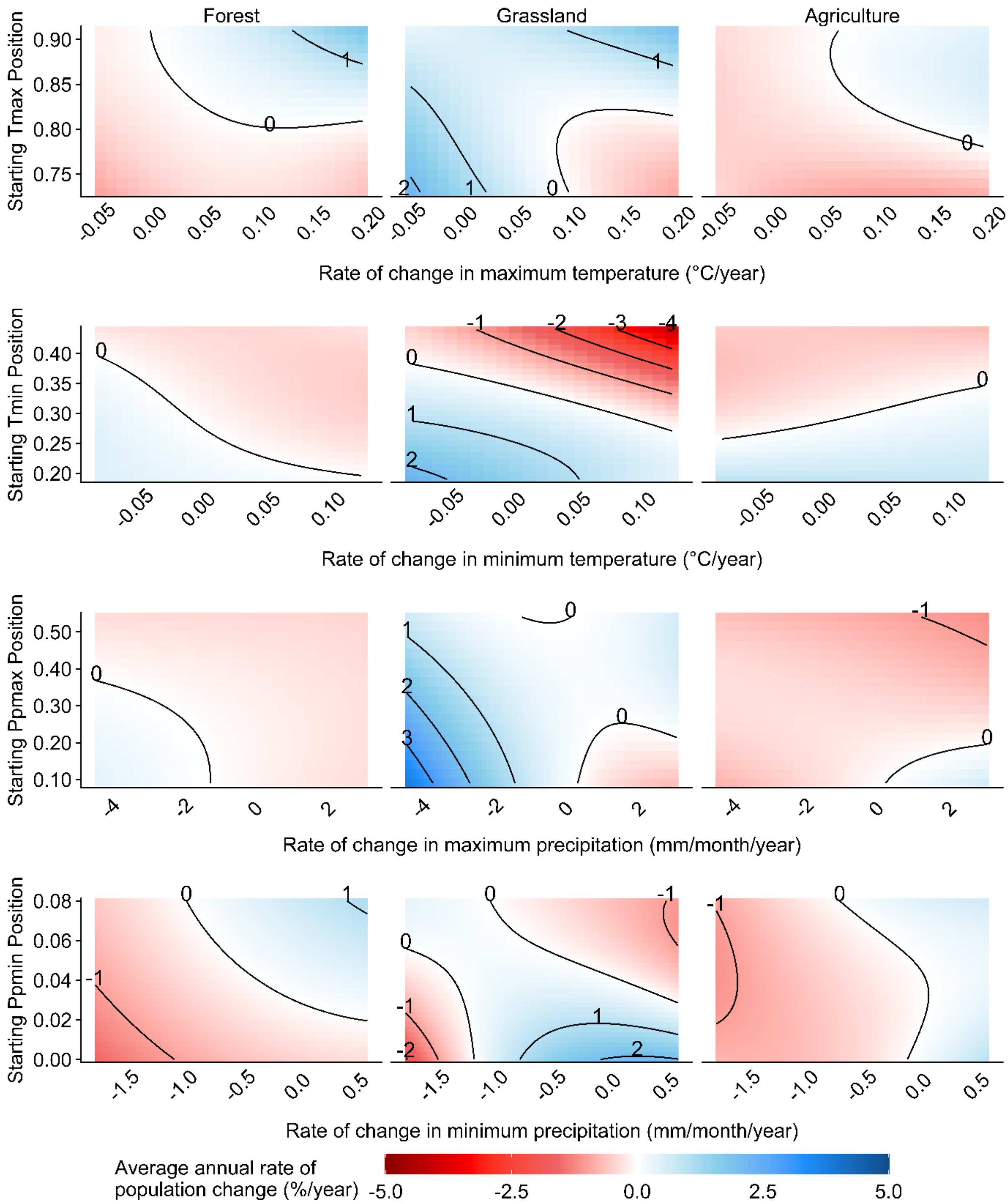

Figure S23: After excluding populations with extreme rates of population change (above and below the upper and lower 97.5th and 2.5th percentile, respectively), the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

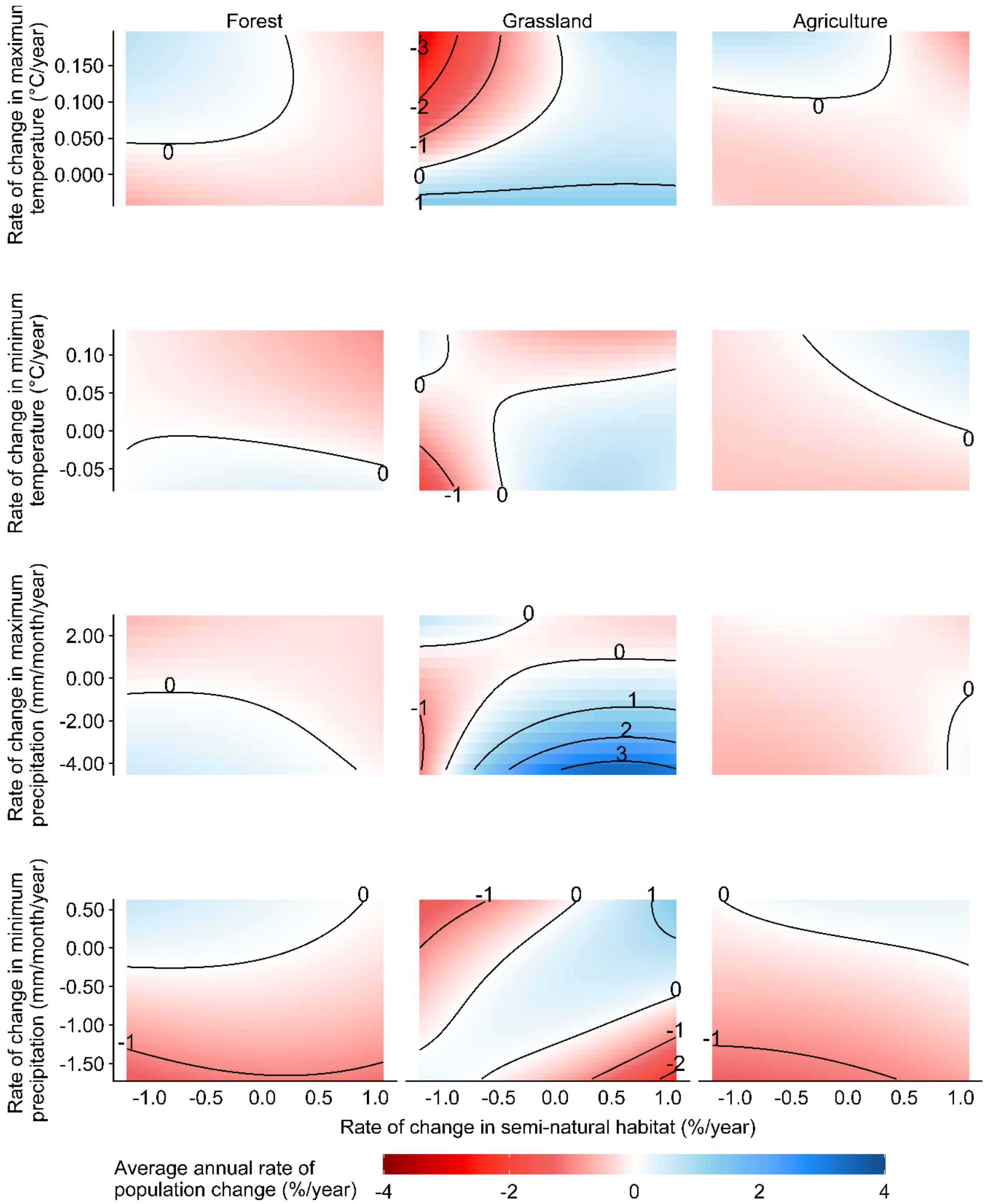

Figure S24: After excluding populations with extreme rates of population change (above and below the upper and lower 97.5th and 2.5th percentile, respectively), the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year).

The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 10: Excluding *Gyps*

There were three species within the dataset from the genus *Gyps* (a genus of Old-World vultures) – *Gyps bengalensis* (11 populations), *G. indicus* (1 population) and *G. tenuirostris* (5 populations). A previous study (Green et al., 2020) found that this genus had a big influence on model estimates, so we removed these species from the dataset, and ran the model described in the main text again. Excluding species from the genus *Gyps* produced a model with a slightly higher marginal R^2 value (by 0.009), but very similar results to the model presented in the main text. The results for the three focal three-way interactions are plotted below (figs. S25-27).

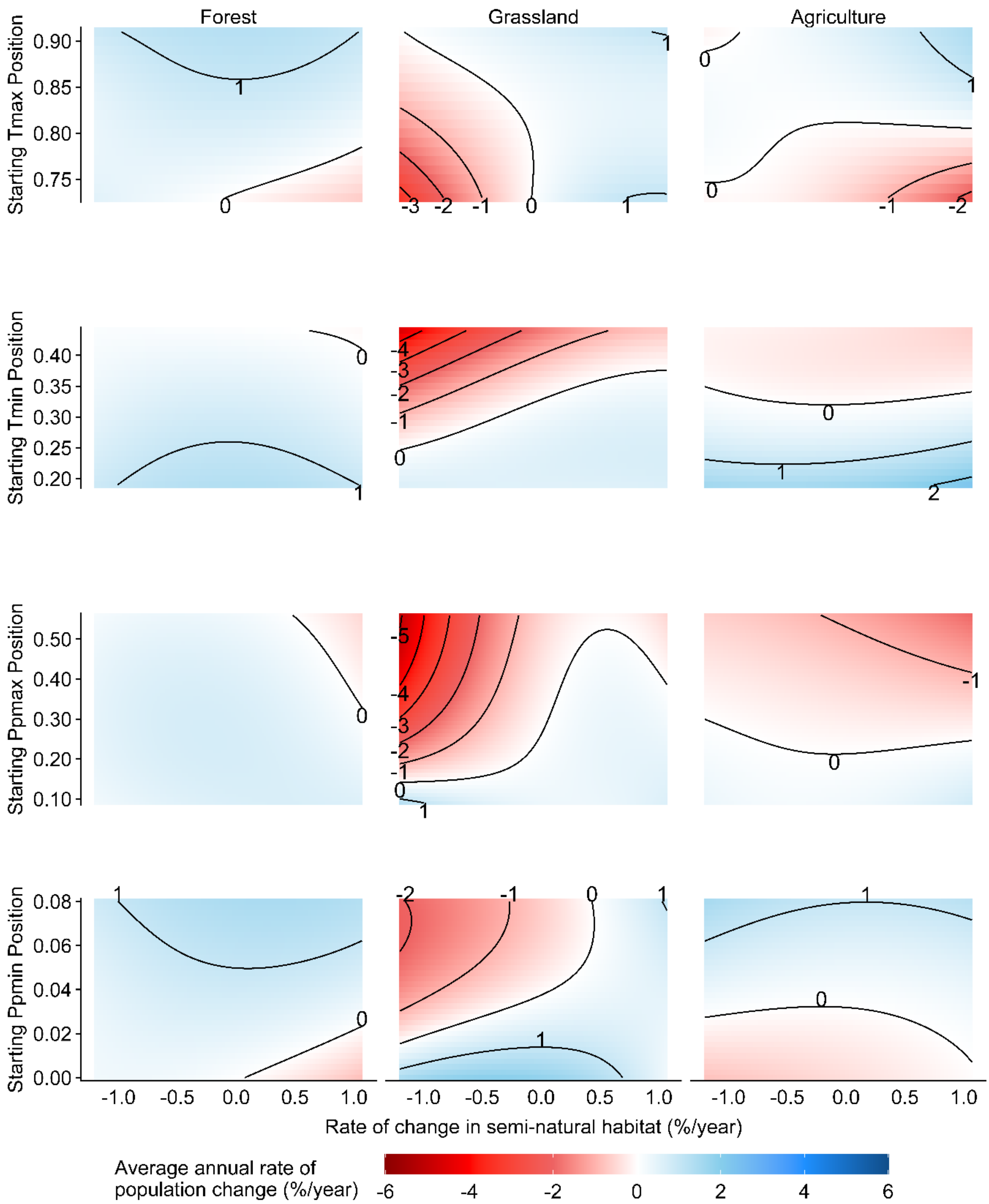

Figure S25: Excluding species within the genus *Gyps*, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and

90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

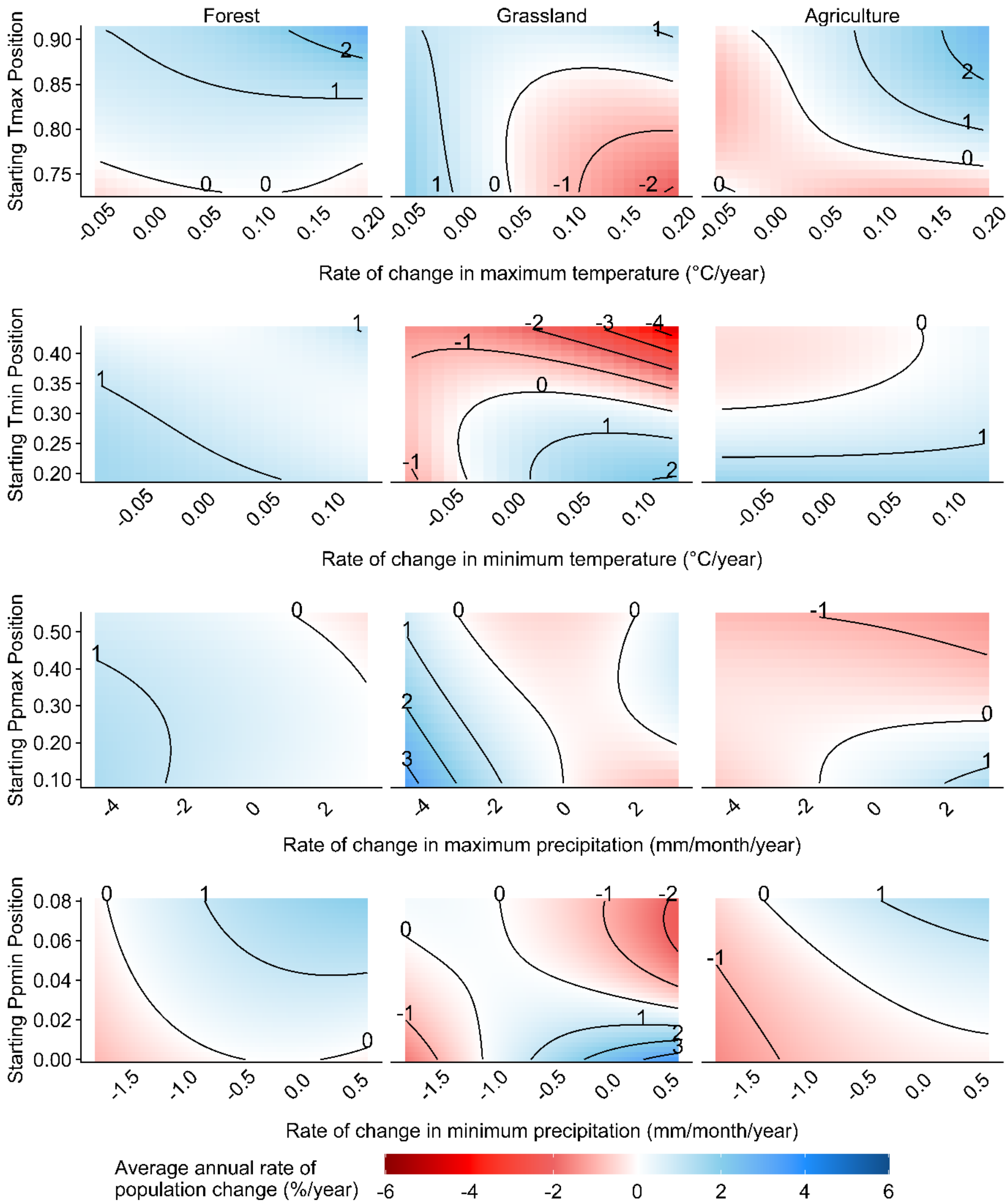

Figure S26: Excluding species within the genus *Gyps*, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

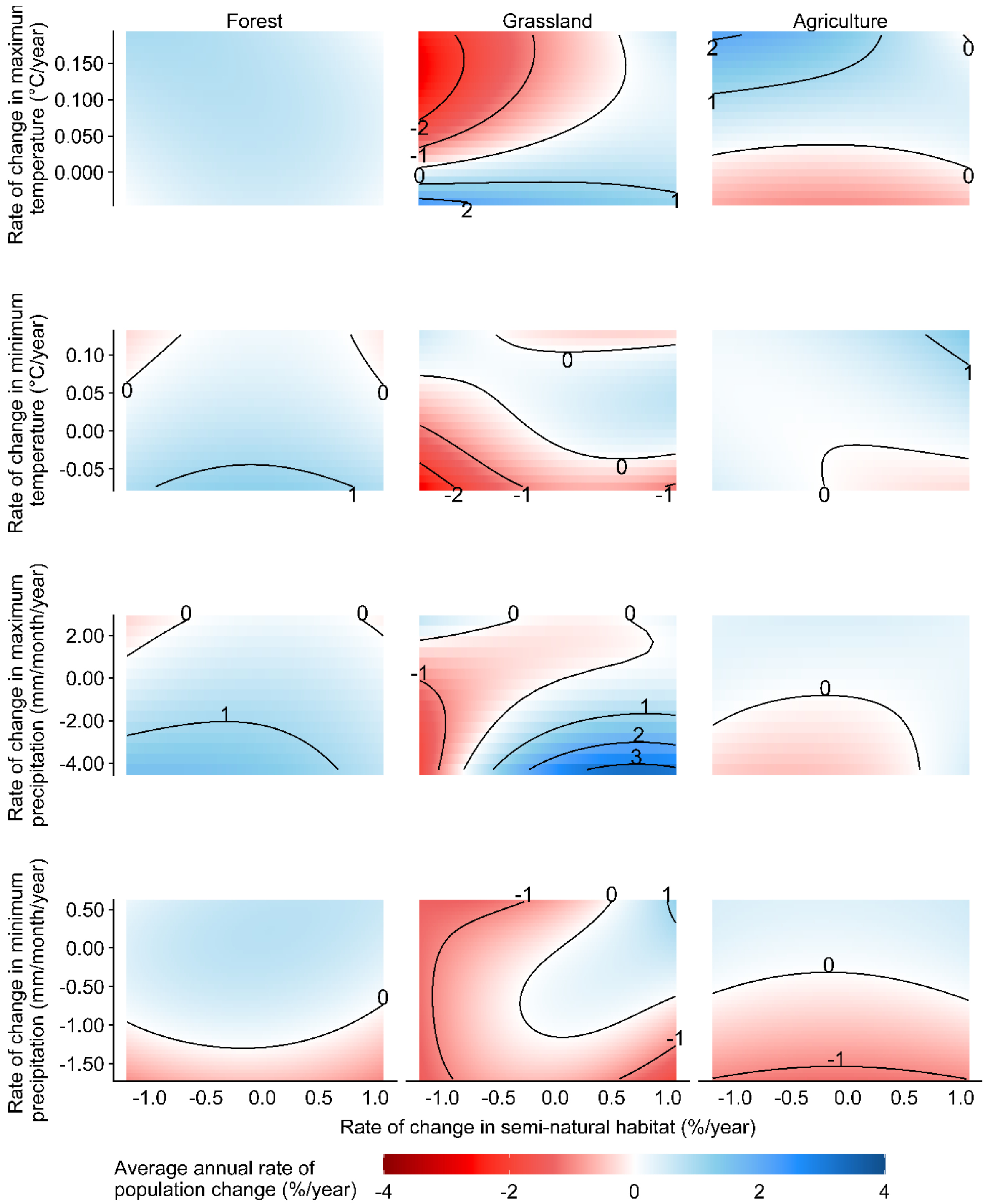

Figure S27: Excluding species within the genus *Gyps*, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x-and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 11: Excluding ectotherms

Ectotherms are suggested to be more sensitive to climatic changes that endotherms, due to the large impacts temperature and precipitation changes can have on ectothermic species' development, movement, reproduction, and biotic interactions (Deutsch et al., 2008; Walther et al., 2002). Consequently, to ensure that ectotherms were not driving any observed patterns in our results, we ran another model with the same structure as our final model, but only including populations of mammals and birds. The results of models excluding ectotherms (figs. S28-30) were very similar to those reported in the main text, although the rates of population change were shifted towards more negative values.

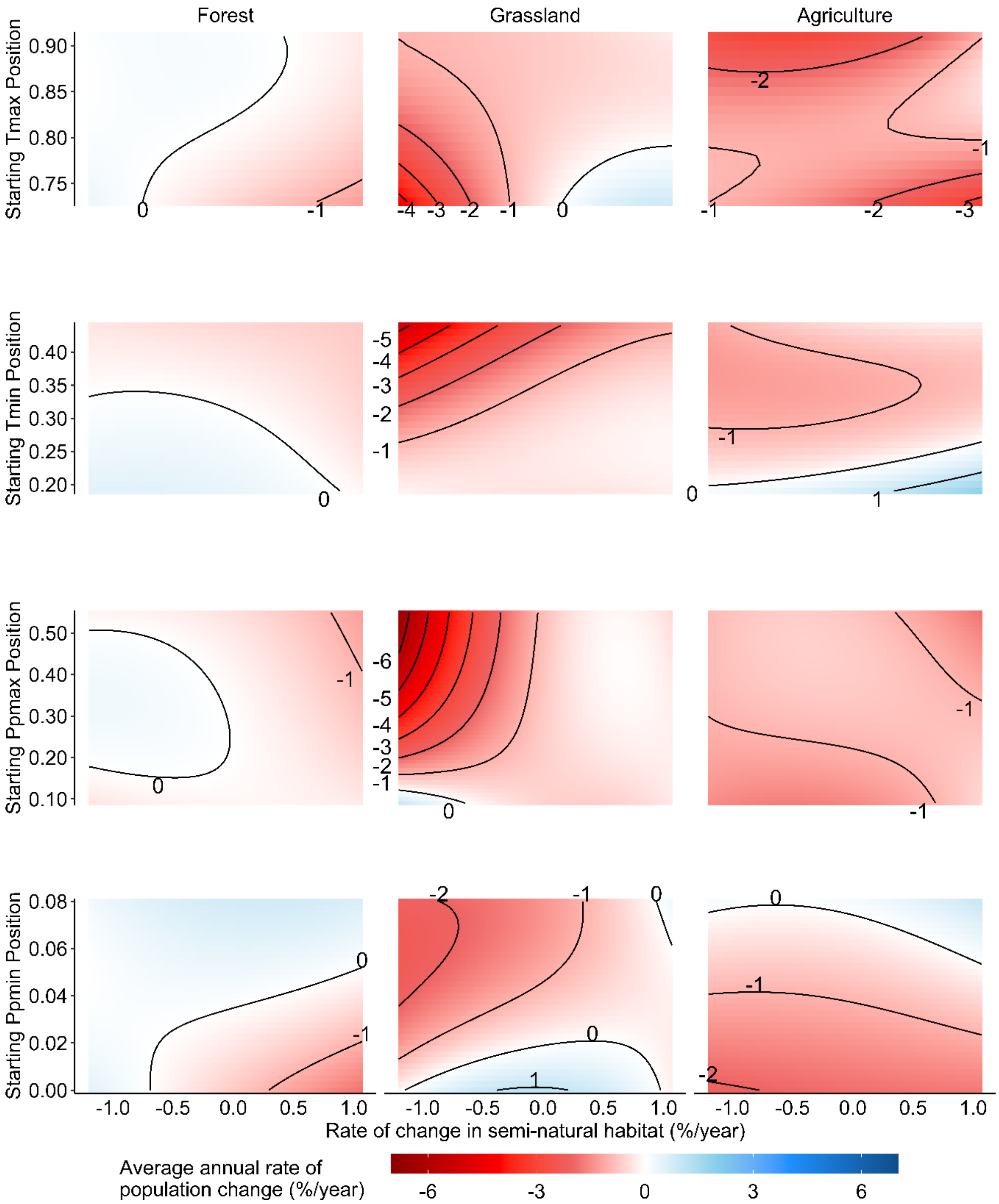

Figure S28: Excluding ectotherms, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and

90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

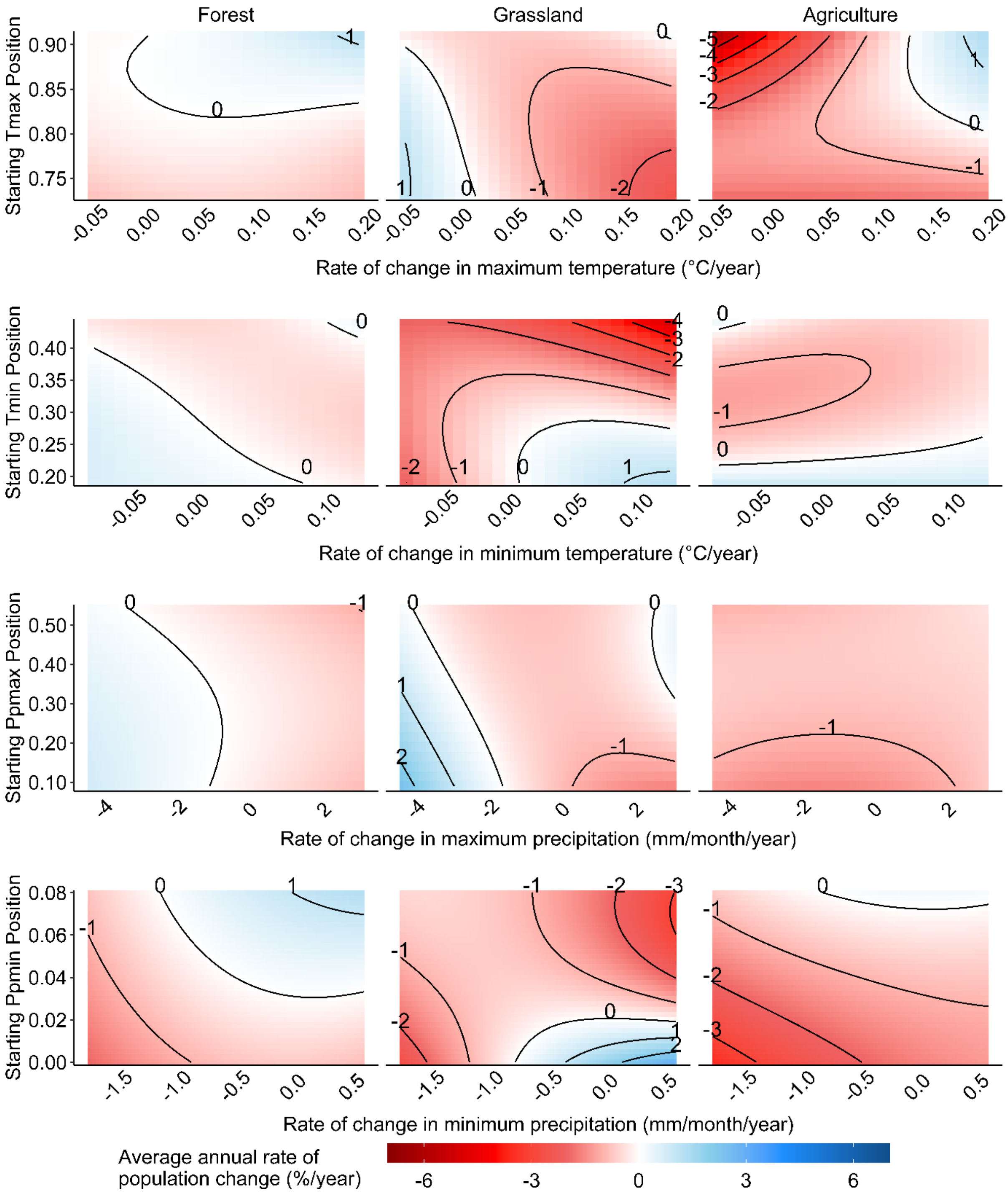

Figure S29: Excluding ectotherms, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

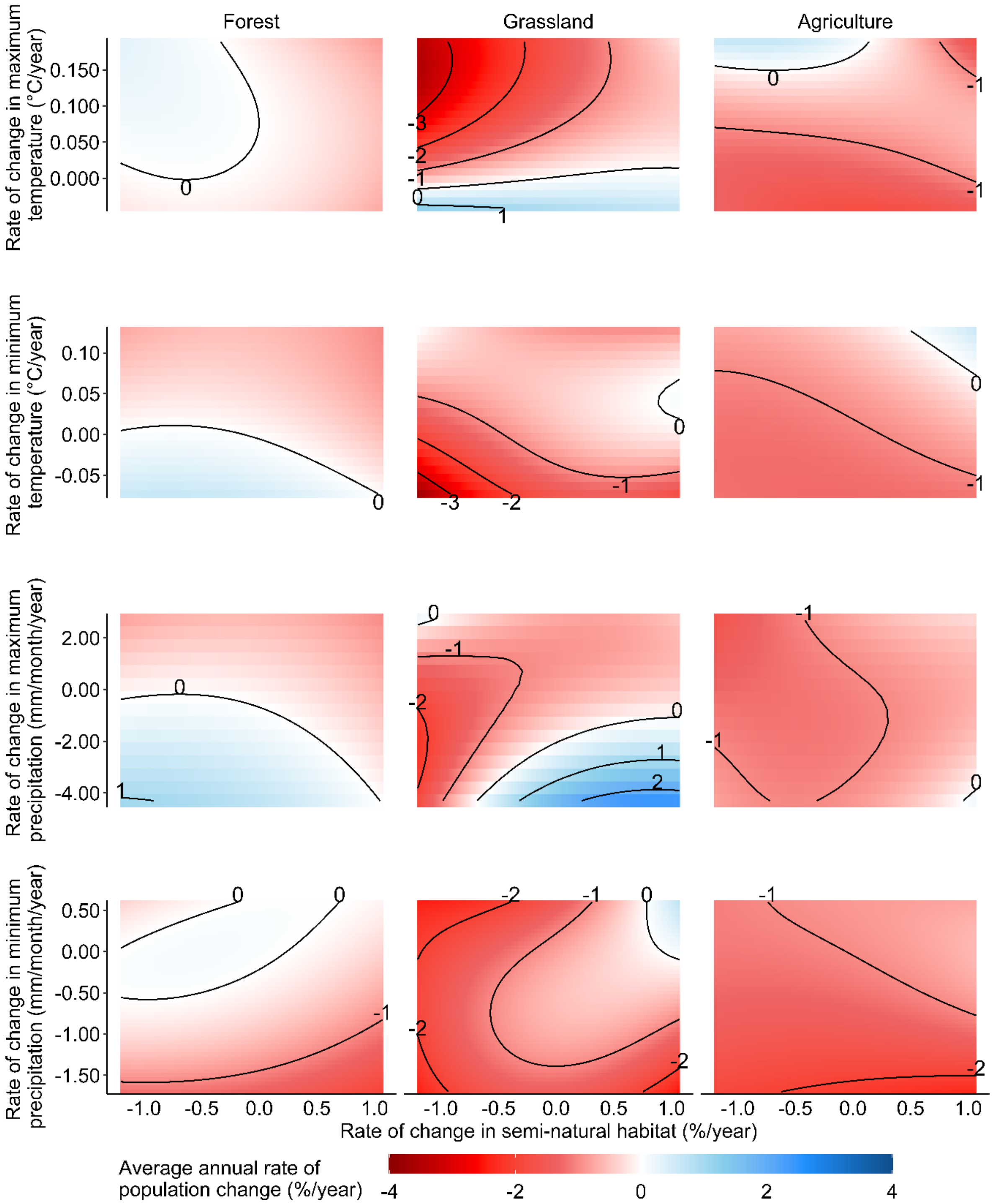

Figure S30: Excluding ectotherms, the average annual rate of population change across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change.

Appendix 12: Including populations recorded outside of their species' ranges

To check the influence of excluding populations outside of their species' ranges (as stated by BirdLife International (2012) and IUCN (2016a-b, 2017a-c, 2018a-b, 2019a-c)), we ran two models, with the same structure as the final model but excluding all terms that included the distance to range edge measure. One model included the populations that were recorded outside of their species' ranges as stated by the BirdLife International (2012) and IUCN (2016a-b, 2017a-c, 2018a-b, 2019a-c) distribution maps, and the other model excluded these populations (i.e., the same populations used to run the final model reported in the main text). This was completed to ensure that removing populations recorded outside of their ranges (completed so that we could include the distance to range edge measure in the candidate models), did not affect our results. The results of the models including populations outside of their reported species' ranges (figs. S31-33) were very similar to those excluding populations outside of their reported species' ranges (although there was a small difference in trend between the models for the interaction of starting land-use type × starting T_{min} position × rate of change in minimum temperature for populations starting in grassland; figs. S34-36).

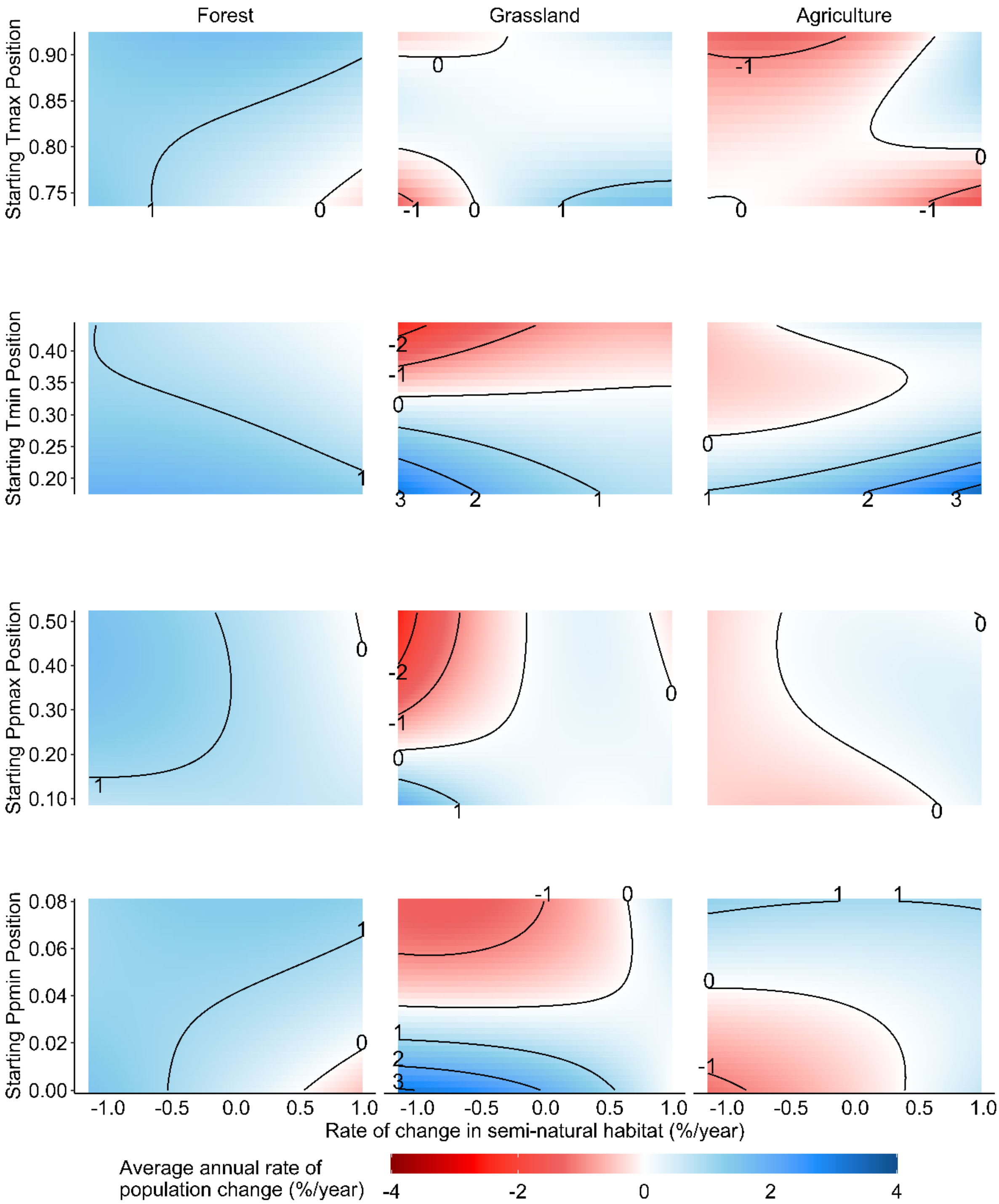

Figure S31: The average annual rate of population change (including populations both inside and outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

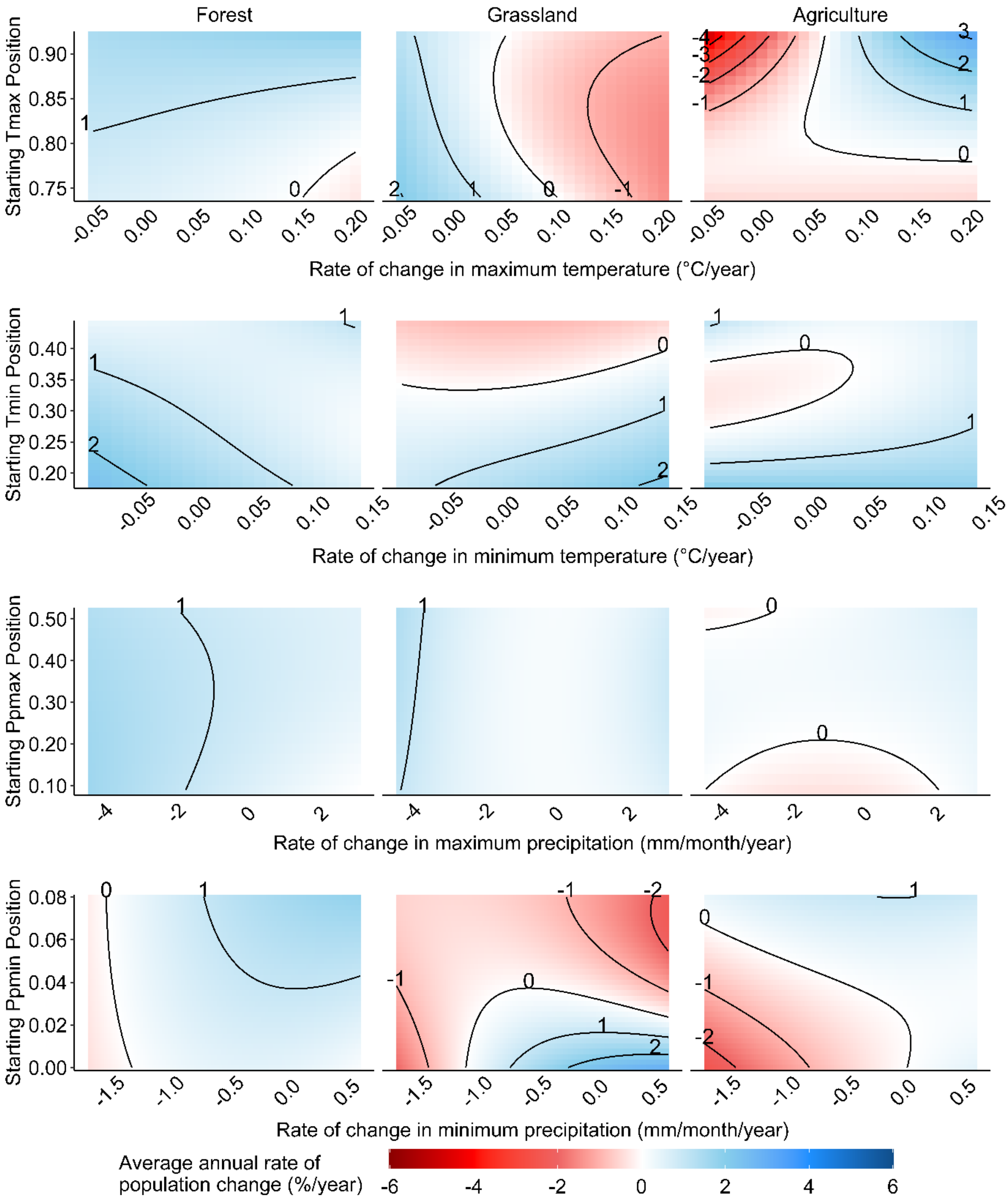

Figure S32: The average annual rate of population change (including populations both inside and outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

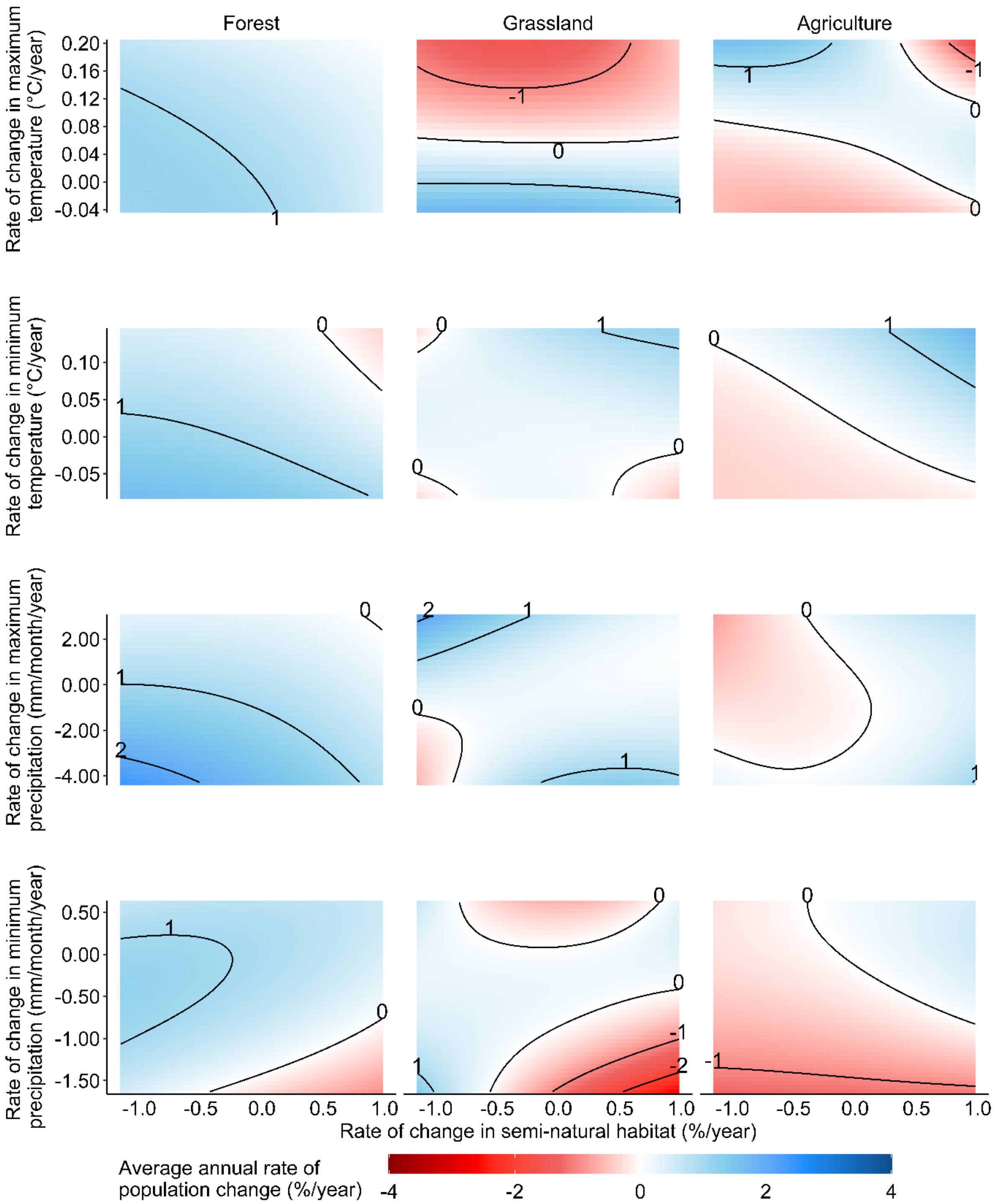

Figure S33: The average annual rate of population change (including populations both inside and outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x- and y-axes are truncated at the 10th and 90th

percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

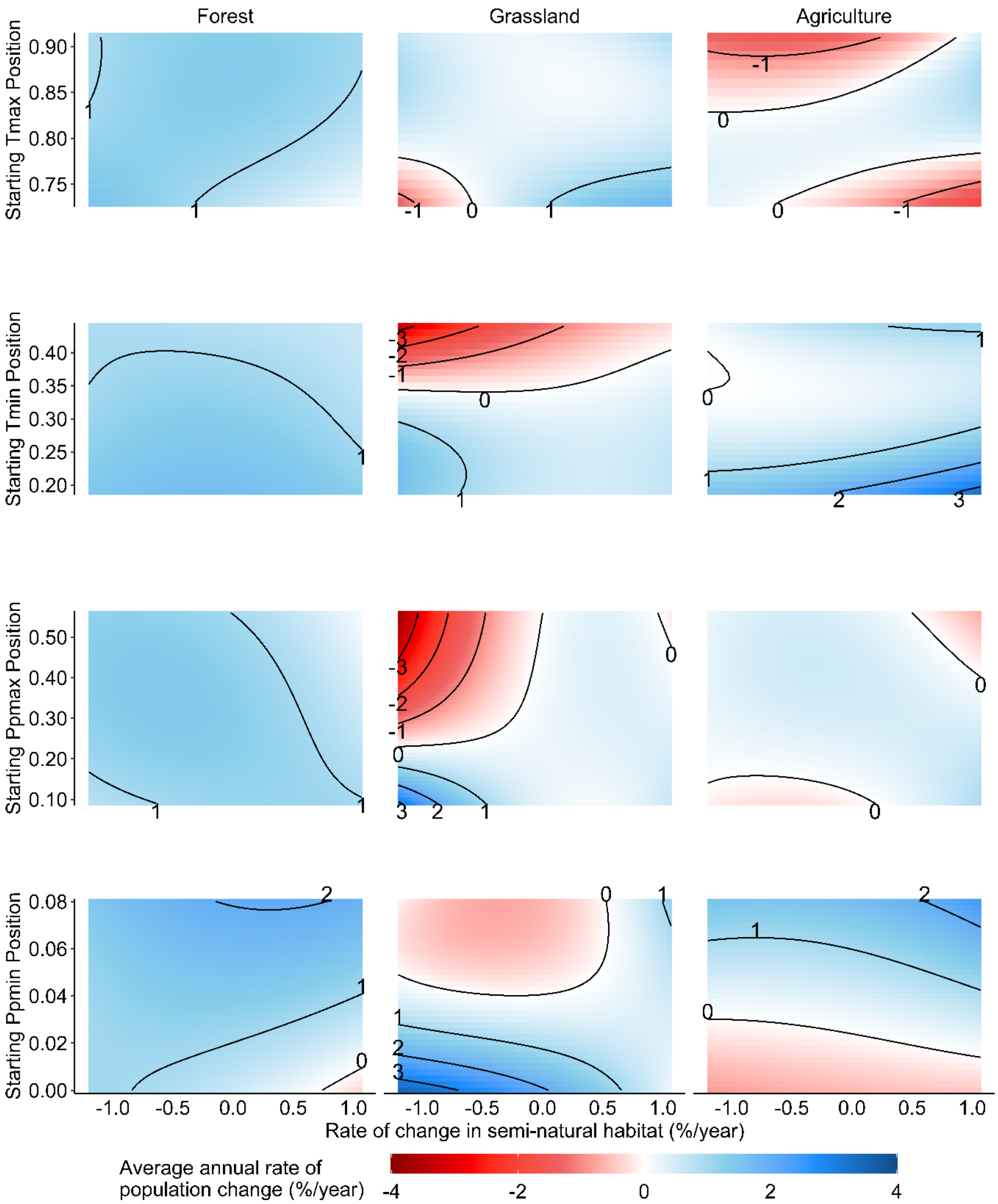

Figure S34: The average annual rate of population change (excluding populations outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius;

and (ii) a population's starting climatic position with regard to maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}) or precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

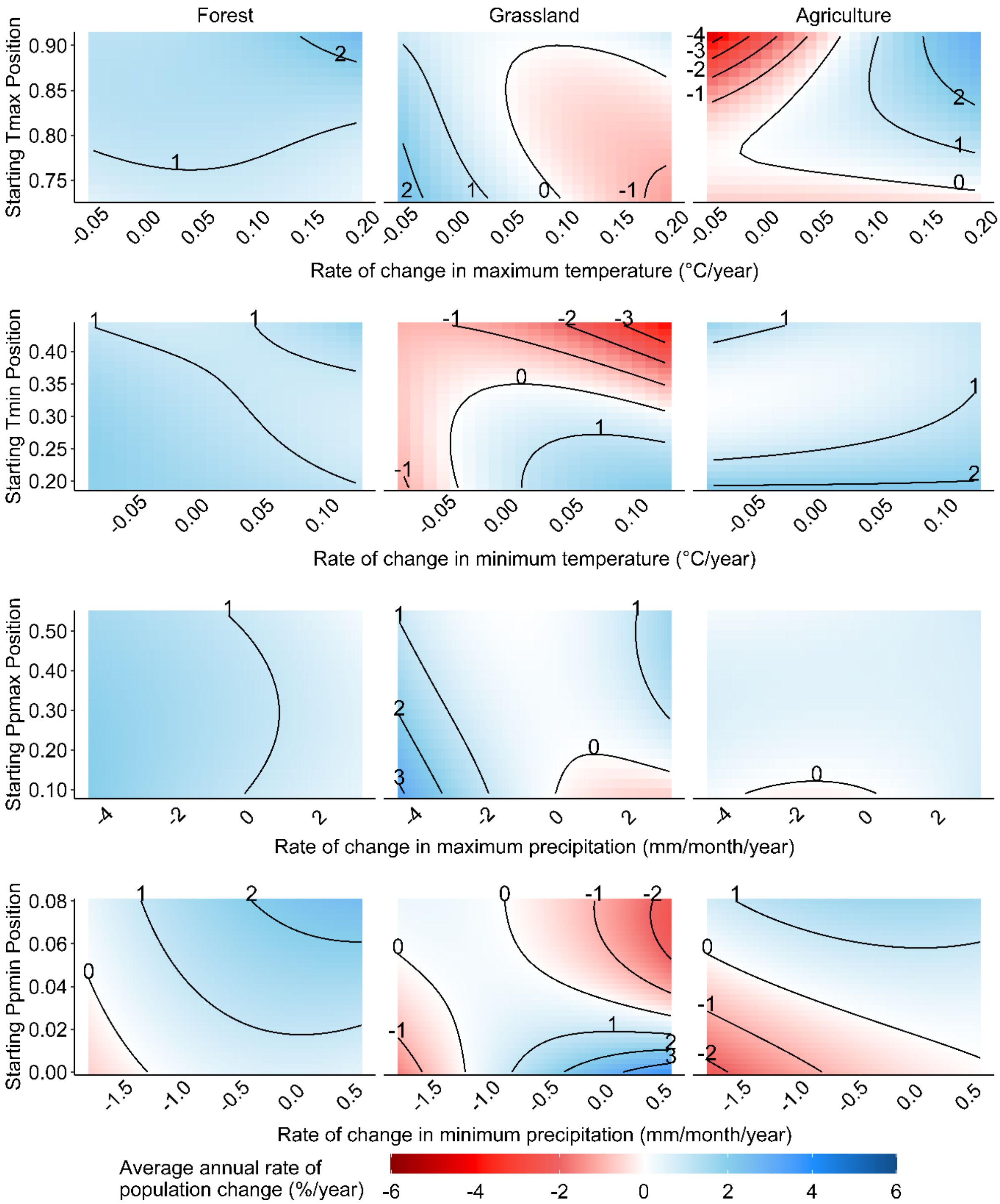

Figure S35: The average annual rate of population change (excluding populations outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in climate; and (ii) a population's starting climatic position. Climatic variables considered were maximum temperature of the warmest month (T_{max}), minimum temperature of the coldest month (T_{min}), precipitation of the wettest month (Pp_{max}), and precipitation of the driest month (Pp_{min}). The x- and y-axes are truncated at the 10th and 90th percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

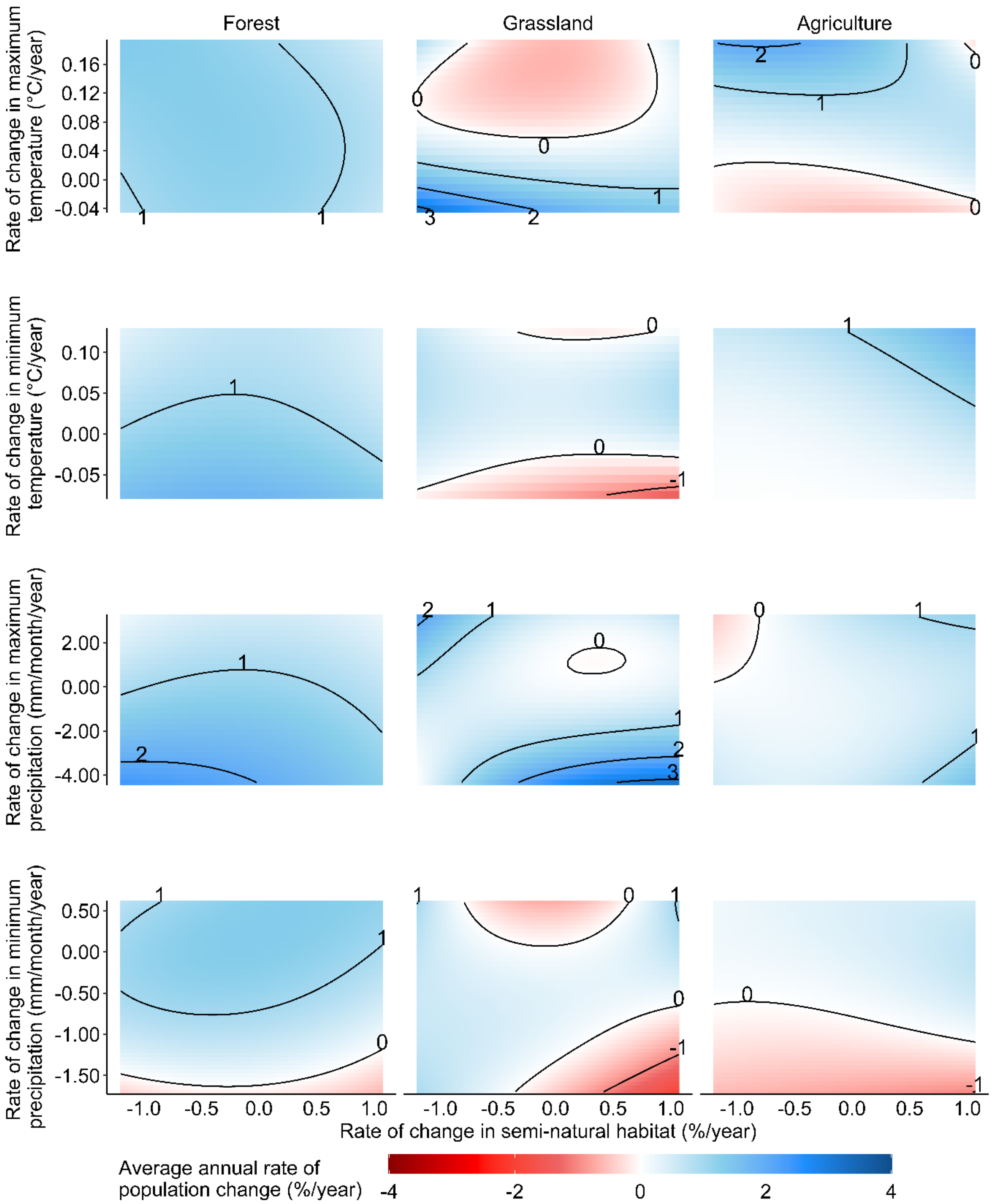

Figure S36: The average annual rate of population change (excluding populations outside of their reported species' ranges) across different starting land-use types, depending on: (i) the average annual rate of change in the percentage of semi-natural habitat within a 1-km radius; and (ii) average annual rate of change in climate with regard to maximum temperature of the warmest month (°C/year), minimum temperature of the coldest month (°C/year), precipitation of the wettest month (monthly mm/year), and precipitation of the driest month (monthly mm/year). The x- and y-axes are truncated at the 10^{th} and 90^{th} percentile of sampled values of each variable. Contour lines (and labels) indicate changes in average annual rate of population change. Terms including distance to range edge were excluded from this model.

Appendix 13: Cross validation tests[WJ19]

We ran leave-one-out cross validation tests of our final model to check there were no overly influential species (figs. S37-38) or locations (figs. S39-40) within our dataset. We did not find any overly influential species or locations.

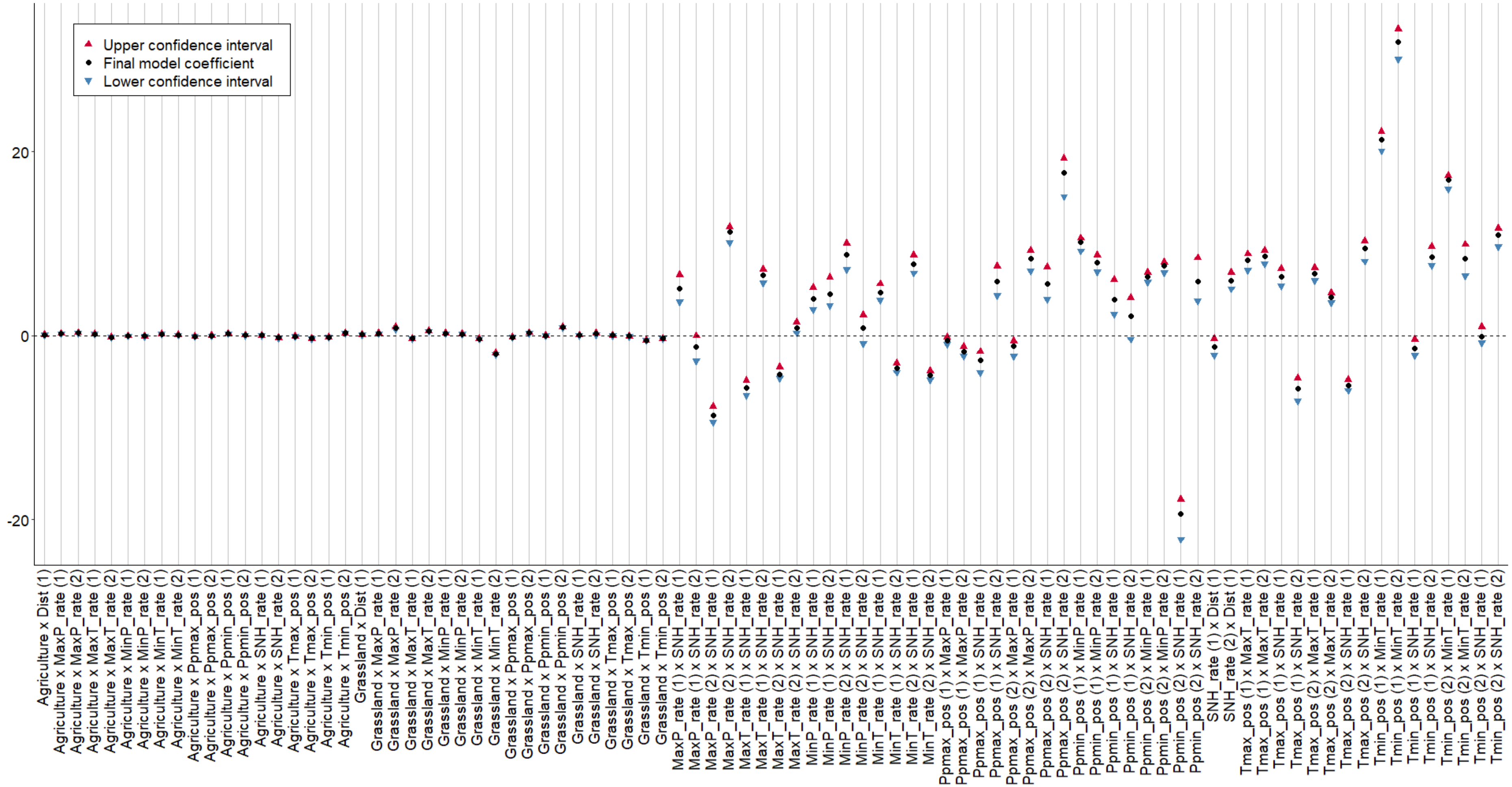

Figure S37: The orthogonal polynomial coefficients of the two-way interactions included in the final model and plotted in the main text, along with the 95% confidence intervals around the estimated coefficients when each species in our dataset was removed one at a time and the model rerun. The final model included starting land-use type (forest [reference level], agriculture, grassland or other), the average annual rate of change in semi-natural habitat (SNH_rate), standardised distance to range edge (Dist), starting climatic positions with regard to T_{max} (Tmax_pos), T_{min} (Tmin_pos), Pp_{max} (Ppmax_pos) and Pp_{min} (Ppmin_pos), average annual rate of change in climate with regard to maximum temperature of the warmest month (MaxT_rate), minimum temperature of the coldest month (MinT_rate), precipitation of the wettest (MaxP_rate) and driest (MinP_rate) months. The continuous variables in the model were run as first-degree (i.e., linear) or second-degree (i.e., quadratic) orthogonal polynomials. Numbers in parentheses refer to the linear (1) or quadratic (2) components of the polynomial terms.

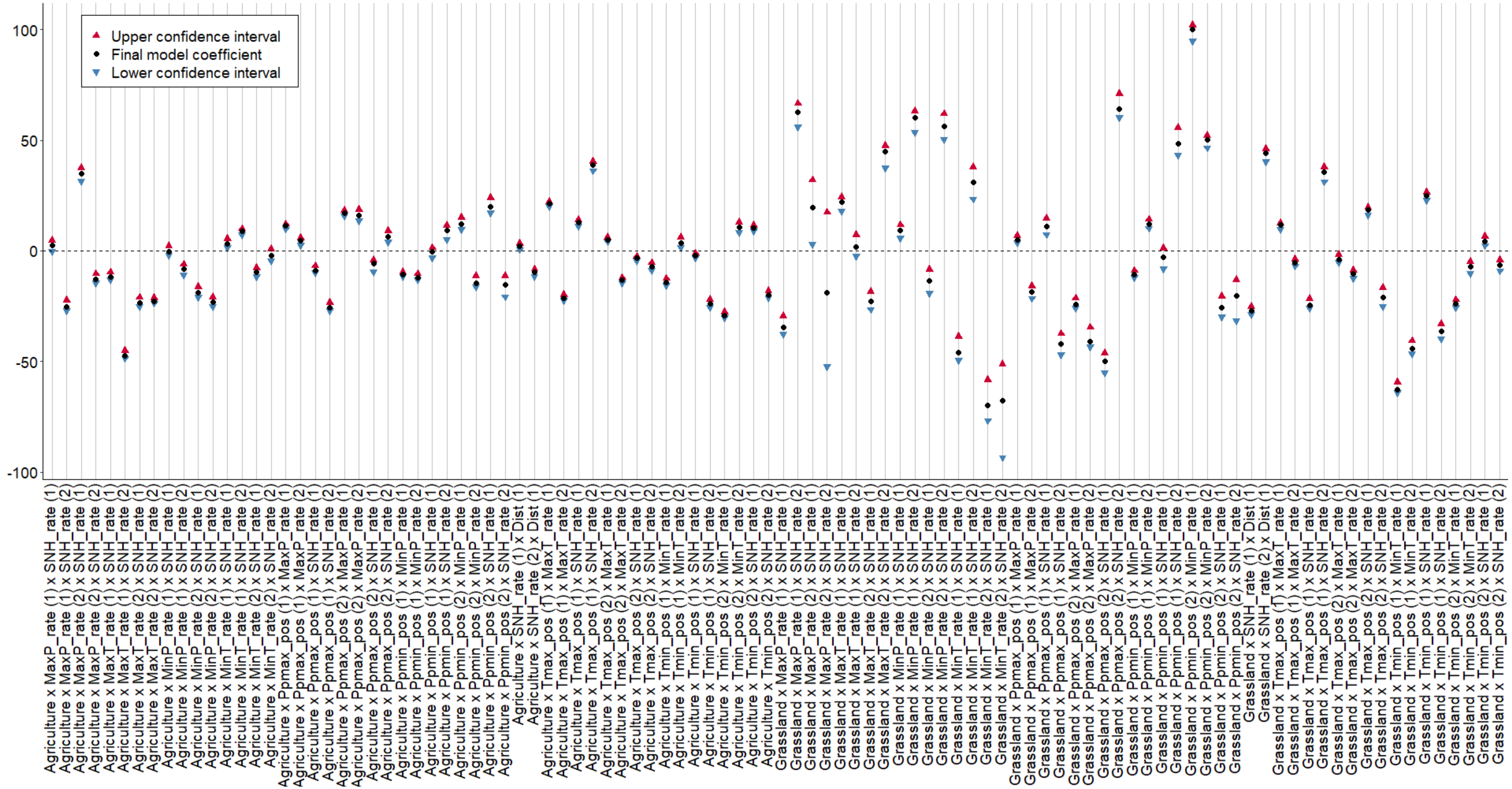

Figure S38: The orthogonal polynomial coefficients of the three-way interactions included in the final model and plotted in the main text, along with the 95% confidence intervals around the estimated coefficients when each species in our dataset was removed one at a time and the model rerun. The final model included starting land-use type (forest [reference level], agriculture, grassland or other), the average annual rate of change in semi-natural habitat (SNH_rate), standardised distance to range edge (Dist), starting climatic positions with regard to T_{max} (Tmax_pos), T_{min}

(Tmin_pos), Pp_{max} (Ppmax_pos) and Pp_{min} (Ppmin_pos), average annual rate of change in climate with regard to maximum temperature of the warmest month (MaxT_rate), minimum temperature of the coldest month (MinT_rate), precipitation of the wettest (MaxP_rate) and driest (MinP_rate) months. The continuous variables in the model were run as first-degree (i.e., linear) or second-degree (i.e., quadratic) orthogonal polynomials. Numbers in parentheses refer to the linear (1) or quadratic (2) components of the polynomial terms.

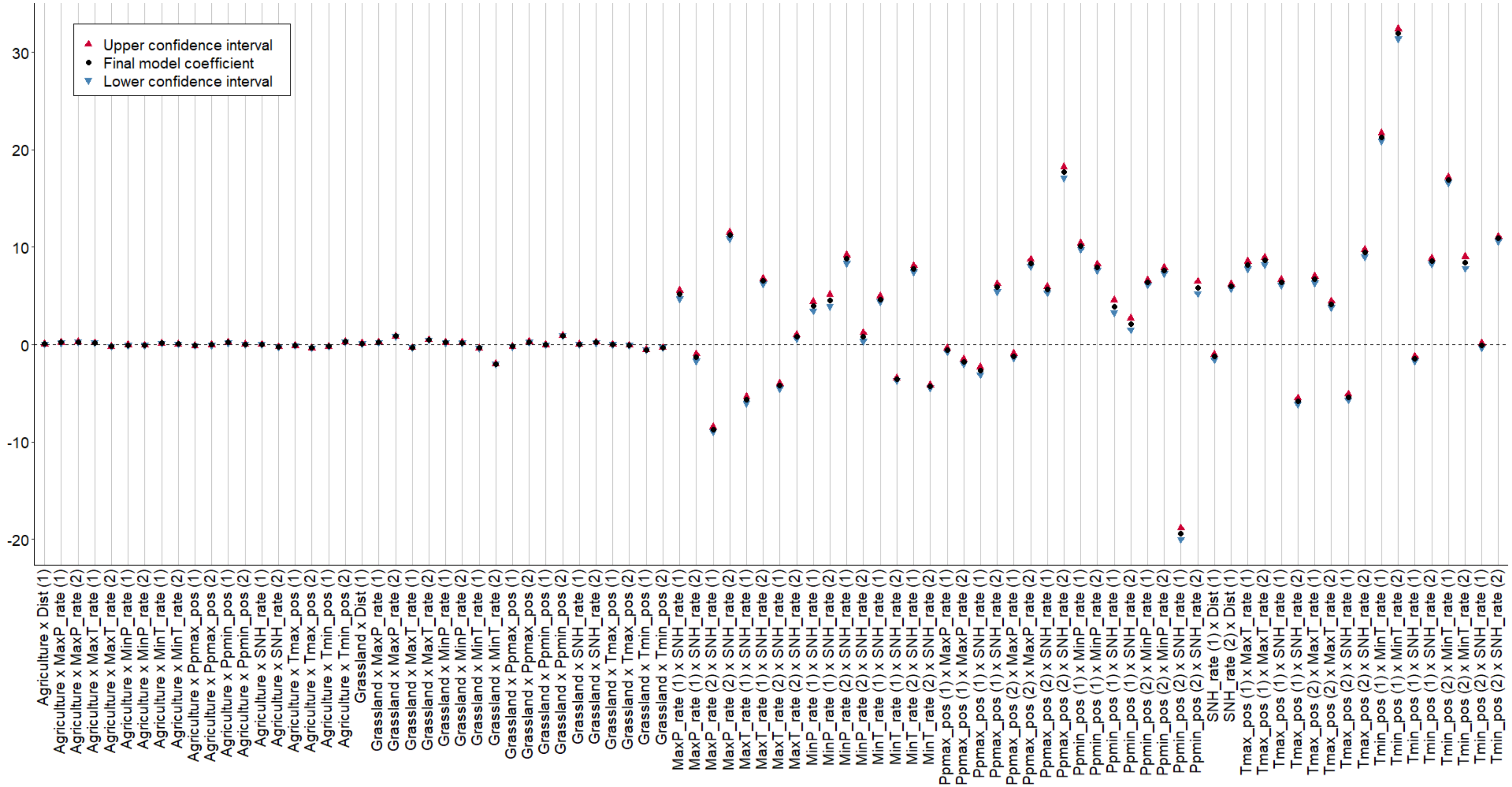

Figure S39: The orthogonal polynomial coefficients of the two-way interactions included in the final model and plotted in the main text, along with the 95% confidence intervals around the estimated coefficients when each location in our dataset was removed one at a time and the model rerun. The final model included starting land-use type (forest [reference level], agriculture, grassland or other), the average annual rate of change in semi-natural habitat (SNH_rate), standardised distance to range edge (Dist), starting climatic positions with regard to T_{max} (Tmax_pos), T_{min}

(Tmin_pos), Pp_{max} (Ppmax_pos) and Pp_{min} (Ppmin_pos), average annual rate of change in climate with regard to maximum temperature of the warmest month (MaxT_rate), minimum temperature of the coldest month (MinT_rate), precipitation of the wettest (MaxP_rate) and driest (MinP_rate) months. The continuous variables in the model were run as first-degree (i.e., linear) or second-degree (i.e., quadratic) orthogonal polynomials. Numbers in parentheses refer to the linear (1) or quadratic (2) components of the polynomial terms.

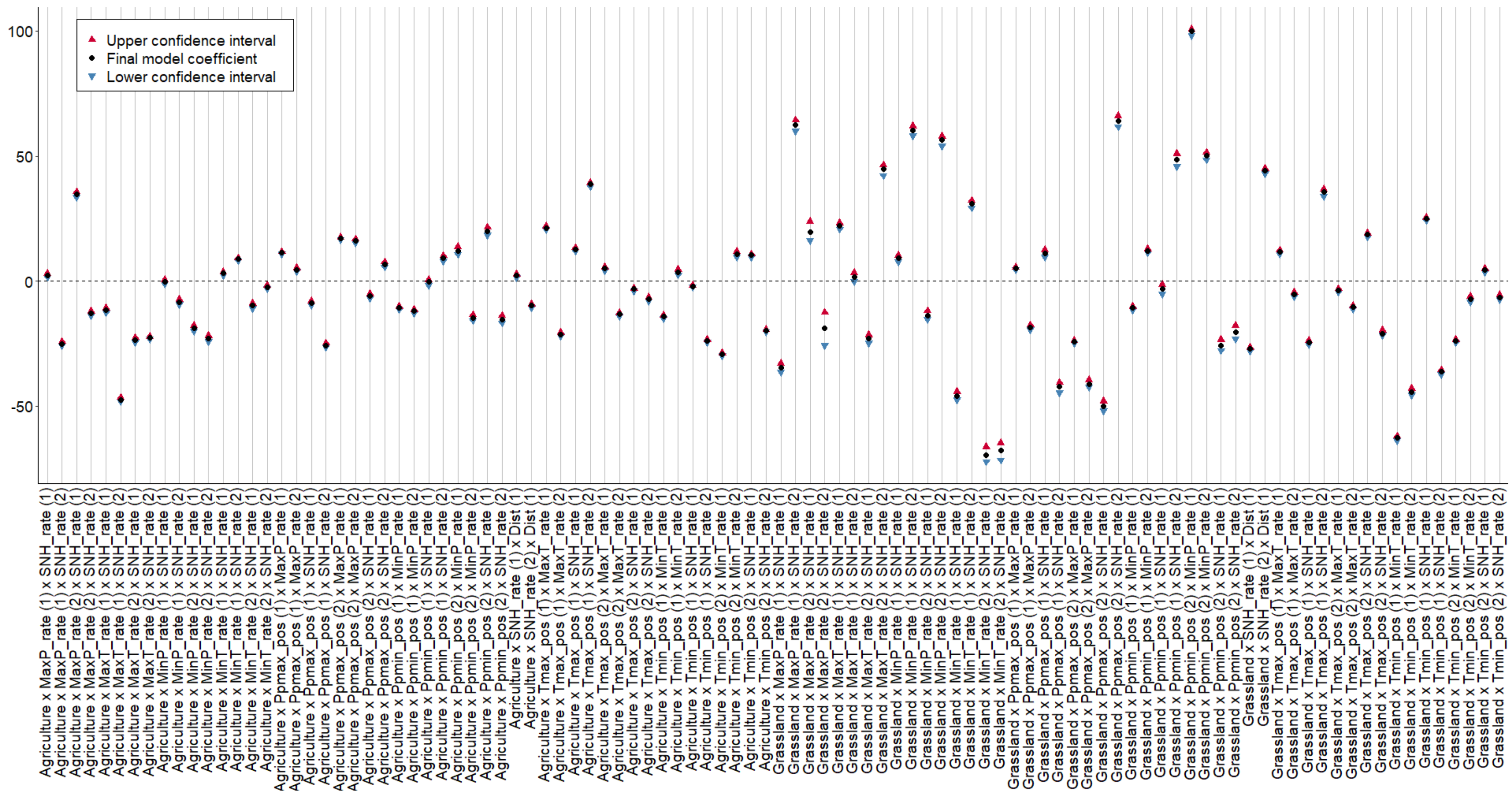

Figure S40: The orthogonal polynomial coefficients of the three-way interactions included in the final model and plotted in the main text, along with the 95% confidence intervals around the estimated coefficients when each location in our dataset was removed one at a time and the model rerun. The final model included starting land-use type (forest [reference level], agriculture, grassland or other), the average annual rate of change in semi-natural habitat (SNH_rate), standardised distance to range edge (Dist), starting climatic positions with regard to T_{max} (Tmax_pos), T_{min} (Tmin_pos), Pp_{max} (Ppmax_pos) and Pp_{min} (Ppmin_pos), average annual rate of change in climate with regard to maximum temperature of the warmest month (MaxT_rate), minimum temperature of the coldest month (MinT_rate), precipitation of the wettest (MaxP_rate) and driest (MinP_rate) months. The continuous variables in the model were run as first-degree (i.e., linear) or second-degree (i.e., quadratic) orthogonal polynomials. Numbers in parentheses refer to the linear (1) or quadratic (2) components of the polynomial terms.

Appendix 14: BioTIME references

Listed below are the references for the four studies extracted from BioTIME whose data were analysed in this study:

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