

SI Figures for *Codistribution as an indicator of whole metacommunity response to environmental change.*

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Simulations

Simulation Setup Example

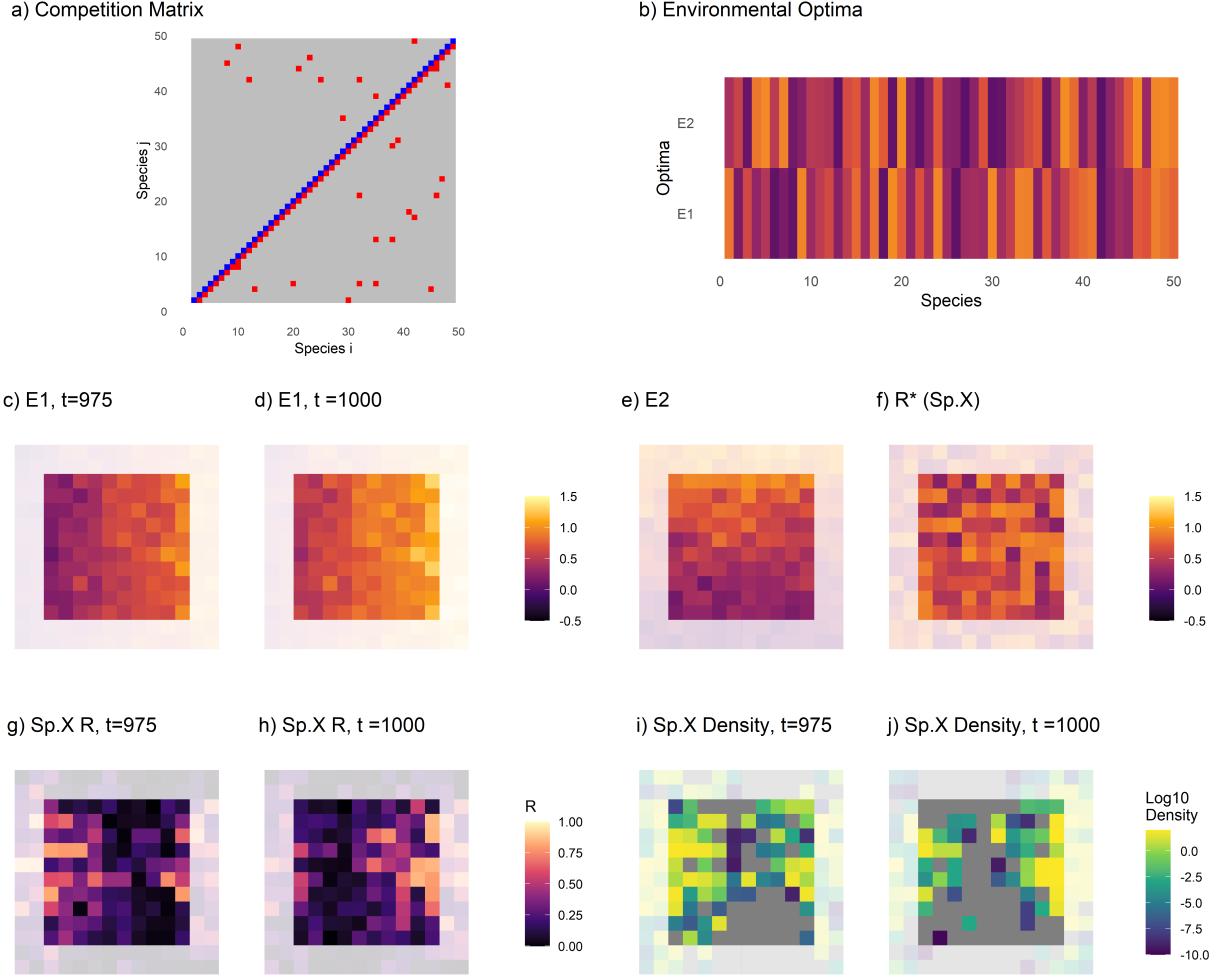


Figure 1: Example illustrations of the simulation model. Values are drawn from the same simulation as illustrated in the main text Figure 2. Values from the peripheral sites not used for the JSDM fitting are shown greyed out. a) Competition matrix, where species are ordered by their (arbitrary) number to show the approach used to specify the distribution of interactions. Blue squares indicate intraspecific interactions b) Species optima for the two environmental variables are random and uncorrelated. c) Pre-change distribution of E_1 variable. This variable increases through time, and could be considered ‘temperature’. d) E_1 variable at $t = 1000$. e) Distribution of E_2 . This variable is fixed throughout the simulation and so could be considered an aspect of geology. f) Distribution of ‘idiosyncratic’ preferences $E_3 (=R^*)$ for the example focal species. This variable adds additional fixed heterogeneity in growth rates distinct for each species to the simulation. g) Growth rate R , of an example species before the onset of climate change. Note the approximately circular shape, but the high degree of heterogeneity. h) Growth rate R of the example species after 25 time steps of climate change ($t = 1000$). Note the leftwards shift in the optimal (bright colours) habitat. i) Pre-climate change distribution of an example species. Note the approximate correspondence with the growth rates, but also infilling due to dispersal mass-effects j) Mid-climate change distribution of the example species. Note the movement lags - the shift leftwards movement is not as noticeable as in the growth rates (h).

Impact of parameters on metacommunity size and occupancy

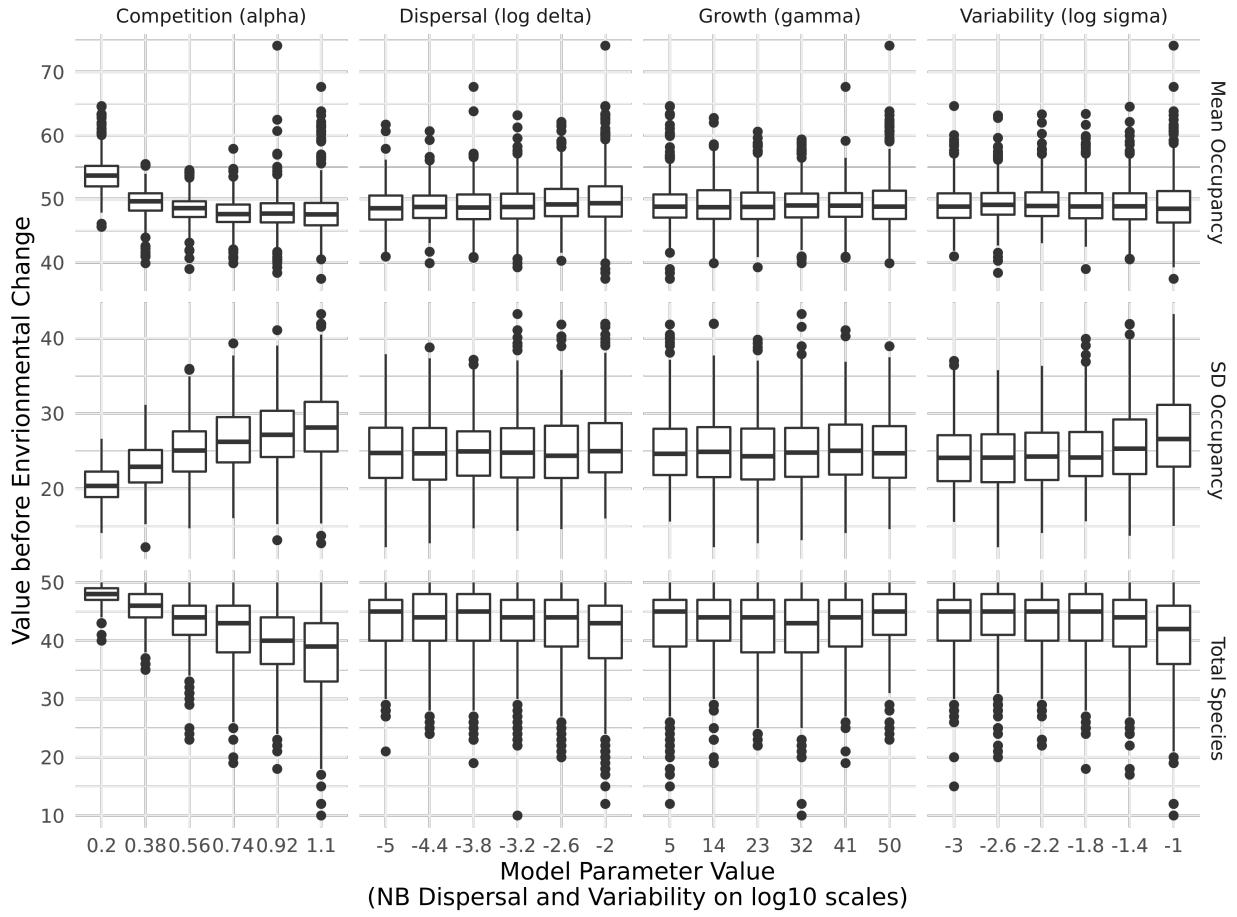


Figure 2: Impact of simulation model parameters on key metacommunity statistics prior to the introduction of environmental change. Only species that are used in the JSDMs are included here, i.e. excluding those that are too rare (or abundant) within the focal squares. Each facet includes all 2460 simulations, but are separated by different responses and driving parameters. Boxplots hinges show 25 and 75th percentiles. Note \log_{10} scales used for dispersal and environmental stochasticity parameters.

Impact of parameters on simulated metacommunity structure

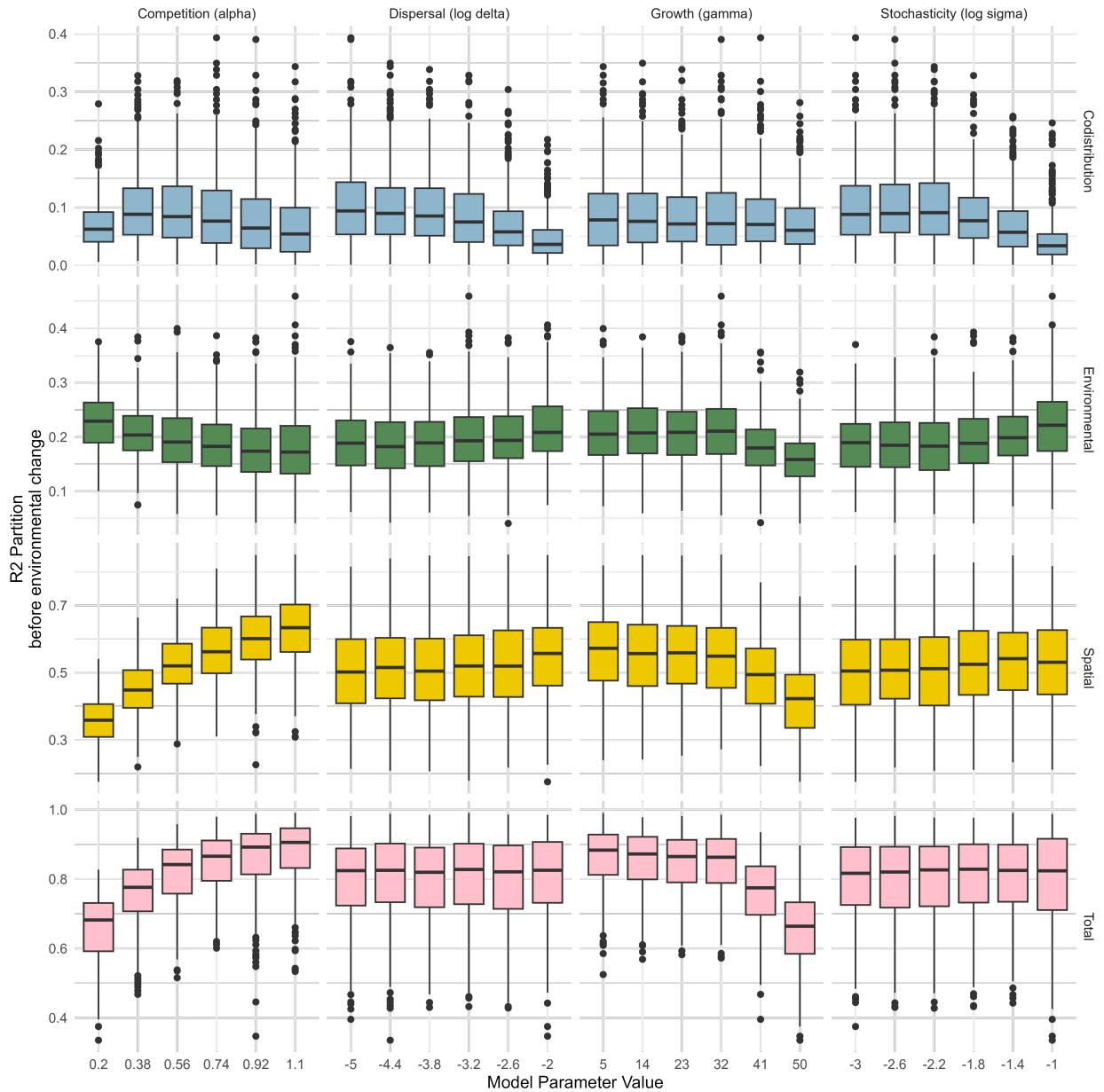


Figure 3: Impact of the model parameters on the simulated metacommunity structure, as assessed by variance partitioning before the introduction of environmental change. Boxplots hinges show 25 and 75th percentiles.

Impact of parameters on shift in simulated metacommunity structure

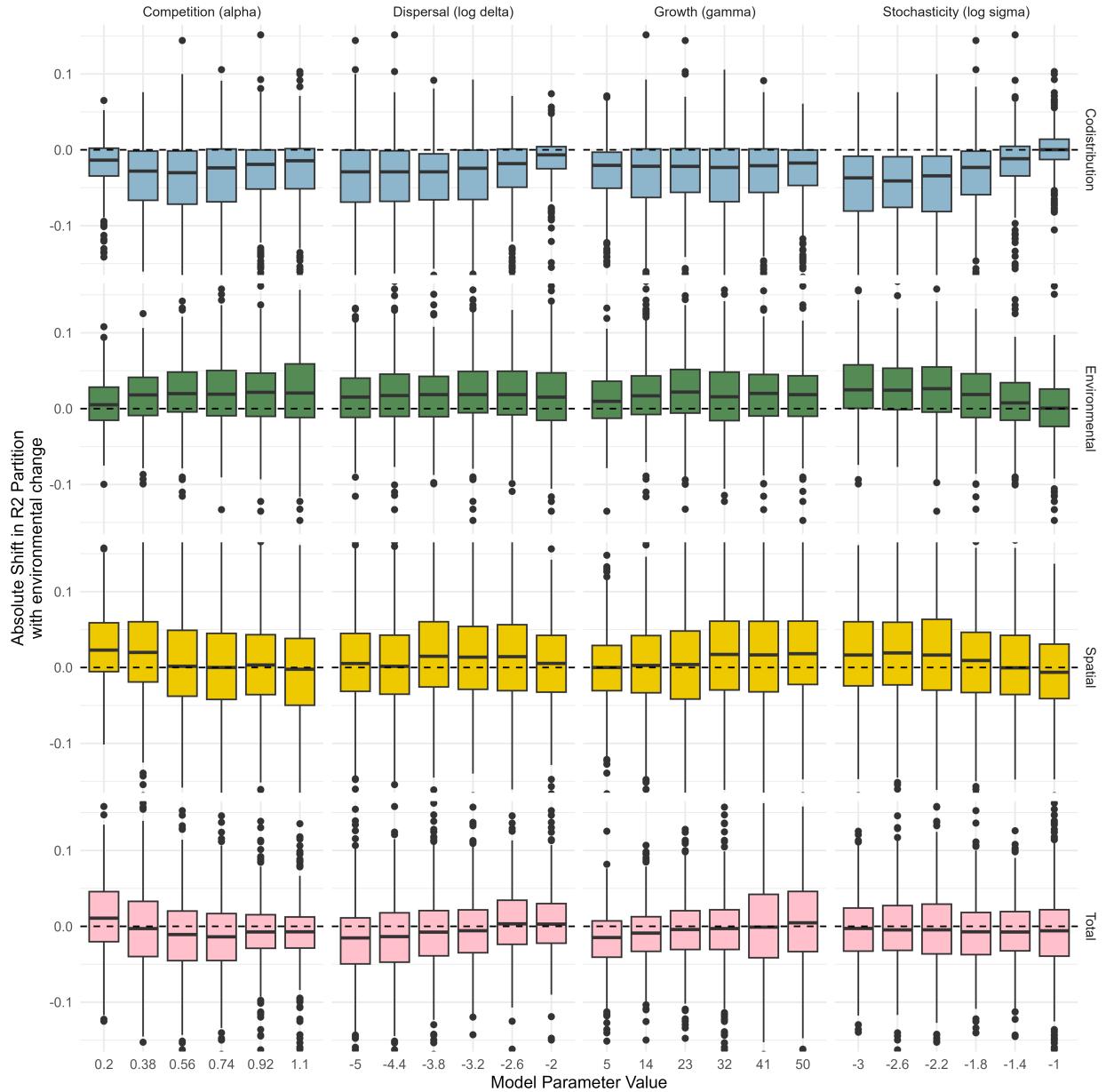


Figure 4: The dependence of shifts in the variance partitioning on the parameters of the simulated metacommunities. Figure 3 in the main text is a summary of this plot. Boxplots hinges show 25 and 75th percentiles.

Impact of false absences on detectability of shift in metacommunity structure

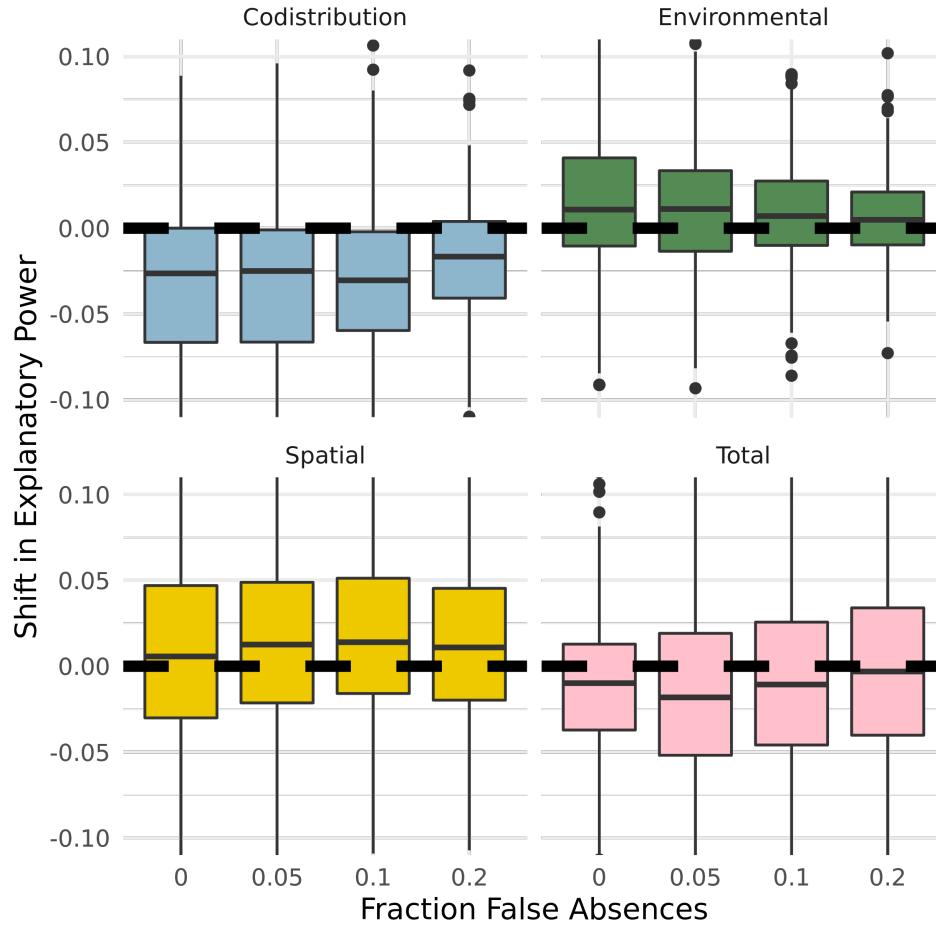


Figure 5: Impact of false absences on the consistent identity of trends. Simulation was run as with the analysis in the main text, but with a reduced spread of core model parameters (δ : $10^{-5}, 10^{-4}, 10^{-3}$; α : 0.3, 0.8, 1.1, γ : 5, 20, 40, σ : $10^{-3}, 10^{-2}, 10^{-1}$), crossed with 4 levels of false absences (0, 0.05, 0.1, 0.2). False absences are introduced by randomly, and independently, switching each presence (i.e. above threshold) to an absence with a given probability. Boxplots hinges show 25 and 75th percentiles.

Butterfly Dataset

Distribution of Sites



Figure 6: Distribution of UKBMS transect sites with sufficient data over focal period to be included in the analysis.

Occupancy Through Time

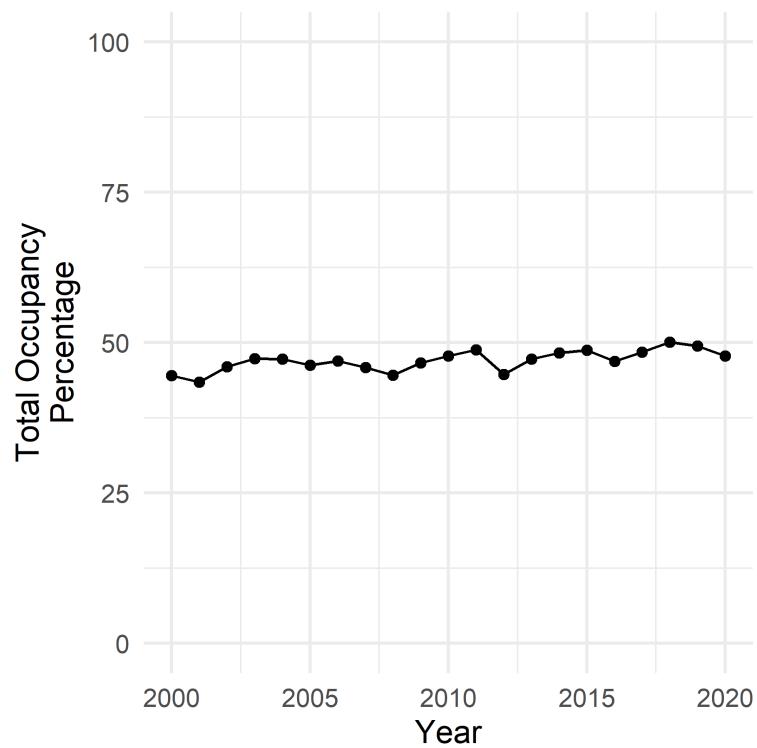


Figure 7: Total occupancy (i.e. total species:site presence records out of maximum possible) of focal butterfly species in focal sites across the time period.

Species-Level Responses

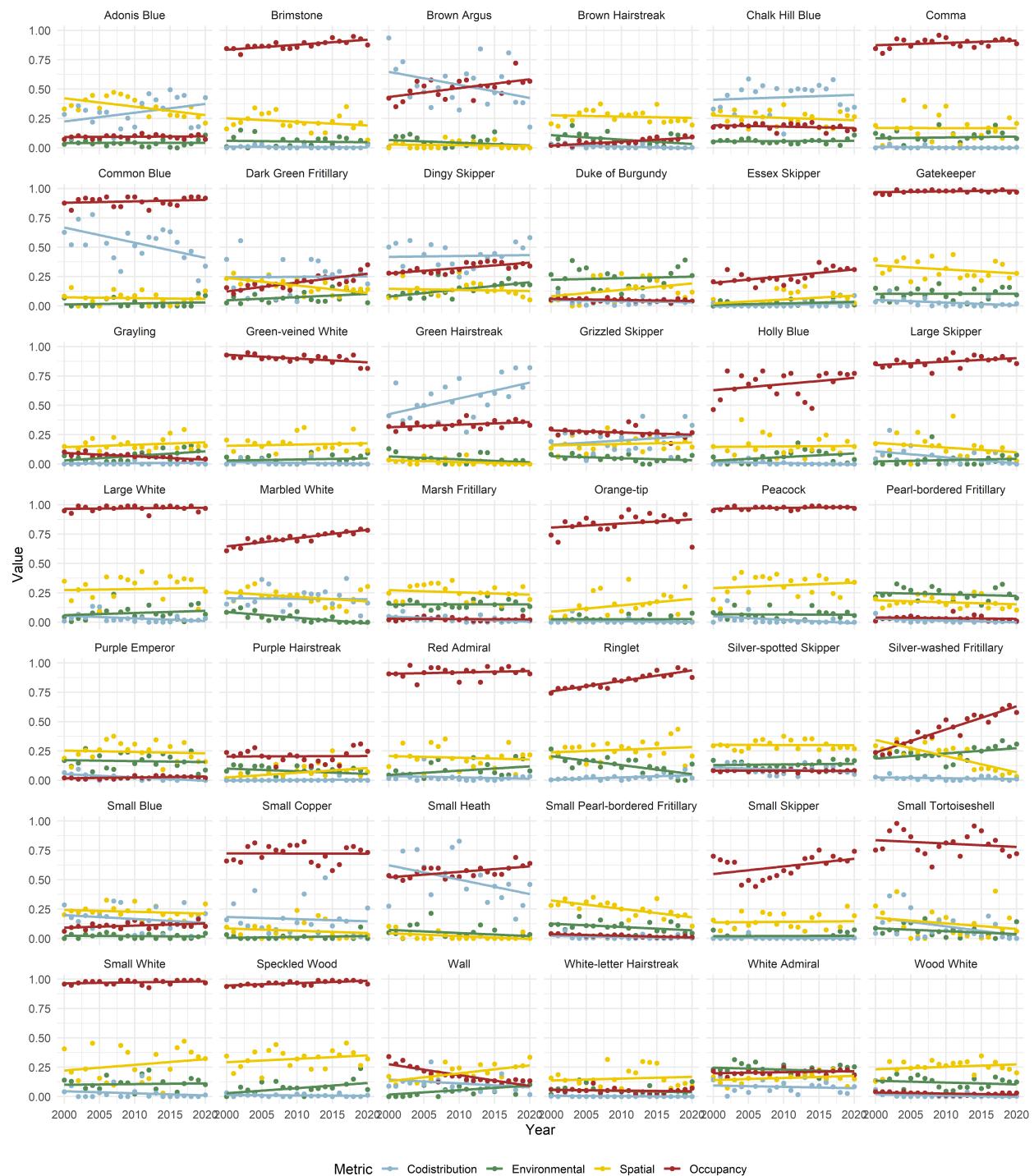


Figure 8: Species-level variance partitioning and species occupancy fraction (out of the 97 focal sites) through time. Note that the changes in the overall variance partitioning are driven by changes in relatively few of the species. However, these species (for example Common Blue and Green Hairstreak) are not necessarily those that are notably changing occupancy through this period.

Species Names

Table 1: Linnean binomials and English common names of focal butterfly species

Scientific Name	English Common Name
<i>Polyommatus bellargus</i>	Adonis Blue
<i>Gonepteryx rhamni</i>	Brimstone
<i>Aricia agestis</i>	Brown Argus
<i>Thecla betulae</i>	Brown Hairstreak
<i>Polyommatus coridon</i>	Chalk Hill Blue
<i>Polygonia c-album</i>	Comma
<i>Polyommatus icarus</i>	Common Blue
<i>Speyeria aglaja</i>	Dark Green Fritillary
<i>Erynnis tages</i>	Dingy Skipper
<i>Hamearis lucina</i>	Duke of Burgundy
<i>Thymelicus lineola</i>	Essex Skipper
<i>Pyronia tithonus</i>	Gatekeeper
<i>Hipparchia semele</i>	Grayling
<i>Pieris napi</i>	Green-veined White
<i>Callophrys rubi</i>	Green Hairstreak
<i>Pyrgus malvae</i>	Grizzled Skipper
<i>Celastrina argiolus</i>	Holly Blue
<i>Ochlodes sylvanus</i>	Large Skipper
<i>Pieris brassicae</i>	Large White
<i>Melanargia galathea</i>	Marbled White
<i>Euphydryas aurinia</i>	Marsh Fritillary
<i>Anthocharis cardamines</i>	Orange-tip
<i>Aglais io</i>	Peacock
<i>Boloria euphrosyne</i>	Pearl-bordered Fritillary
<i>Apatura iris</i>	Purple Emperor
<i>Favonius quercus</i>	Purple Hairstreak
<i>Vanessa atalanta</i>	Red Admiral
<i>Aphantopus hyperantus</i>	Ringlet
<i>Hesperia comma</i>	Silver-spotted Skipper
<i>Argynnis paphia</i>	Silver-washed Fritillary
<i>Cupido minimus</i>	Small Blue
<i>Lycaena phlaeas</i>	Small Copper
<i>Coenonympha pamphilus</i>	Small Heath
<i>Boloria selene</i>	Small Pearl-bordered Fritillary
<i>Thymelicus sylvestris</i>	Small Skipper
<i>Aglais urticae</i>	Small Tortoiseshell
<i>Pieris rapae</i>	Small White
<i>Pararge aegeria</i>	Speckled Wood
<i>Lasiommata megera</i>	Wall
<i>Satyrium w-album</i>	White-letter Hairstreak
<i>Limenitis camilla</i>	White Admiral
<i>Leptidea sinapis</i>	Wood White

Fitted Environmental Coefficients

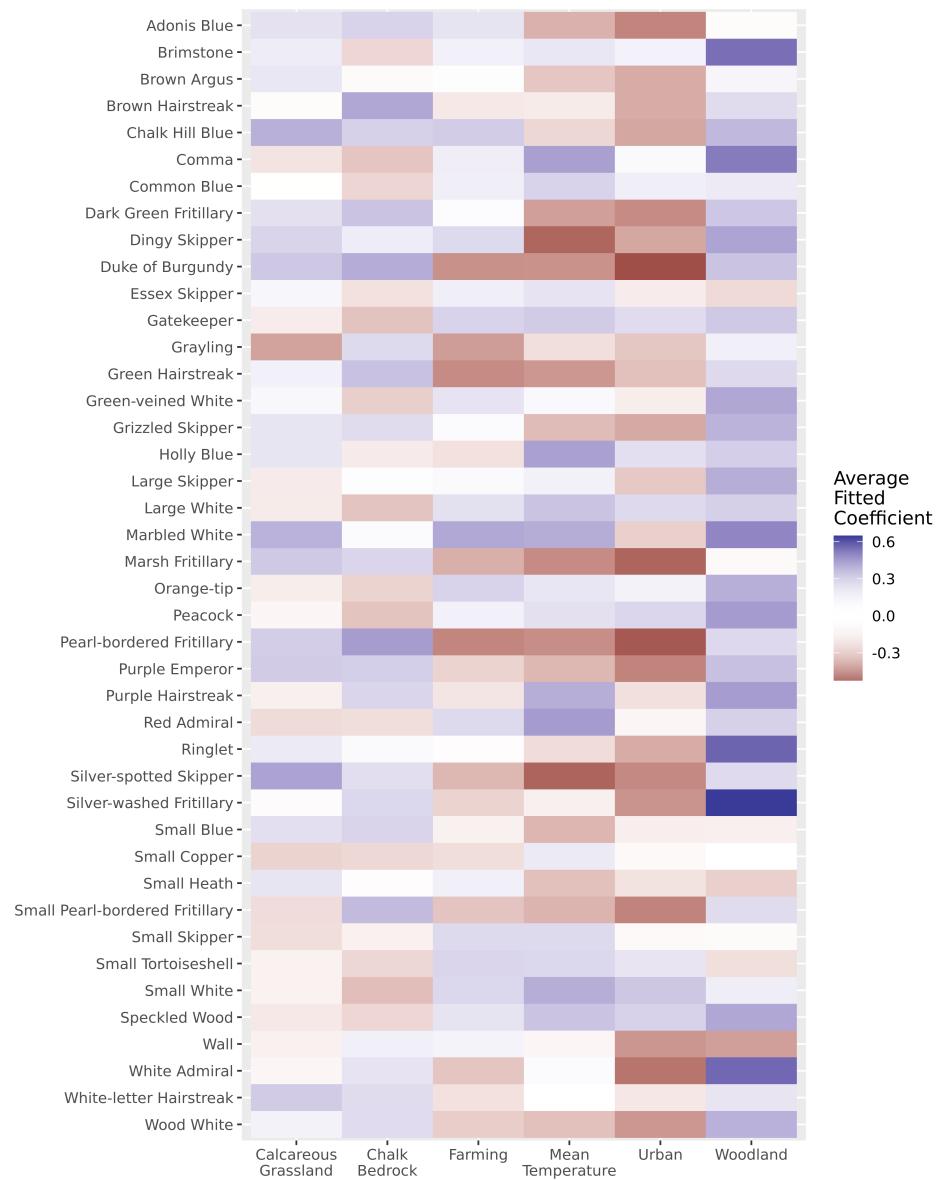


Figure 9: Butterfly fitted species-level environmental coefficients, averaged across all 21 years.

Fitted Species Associations

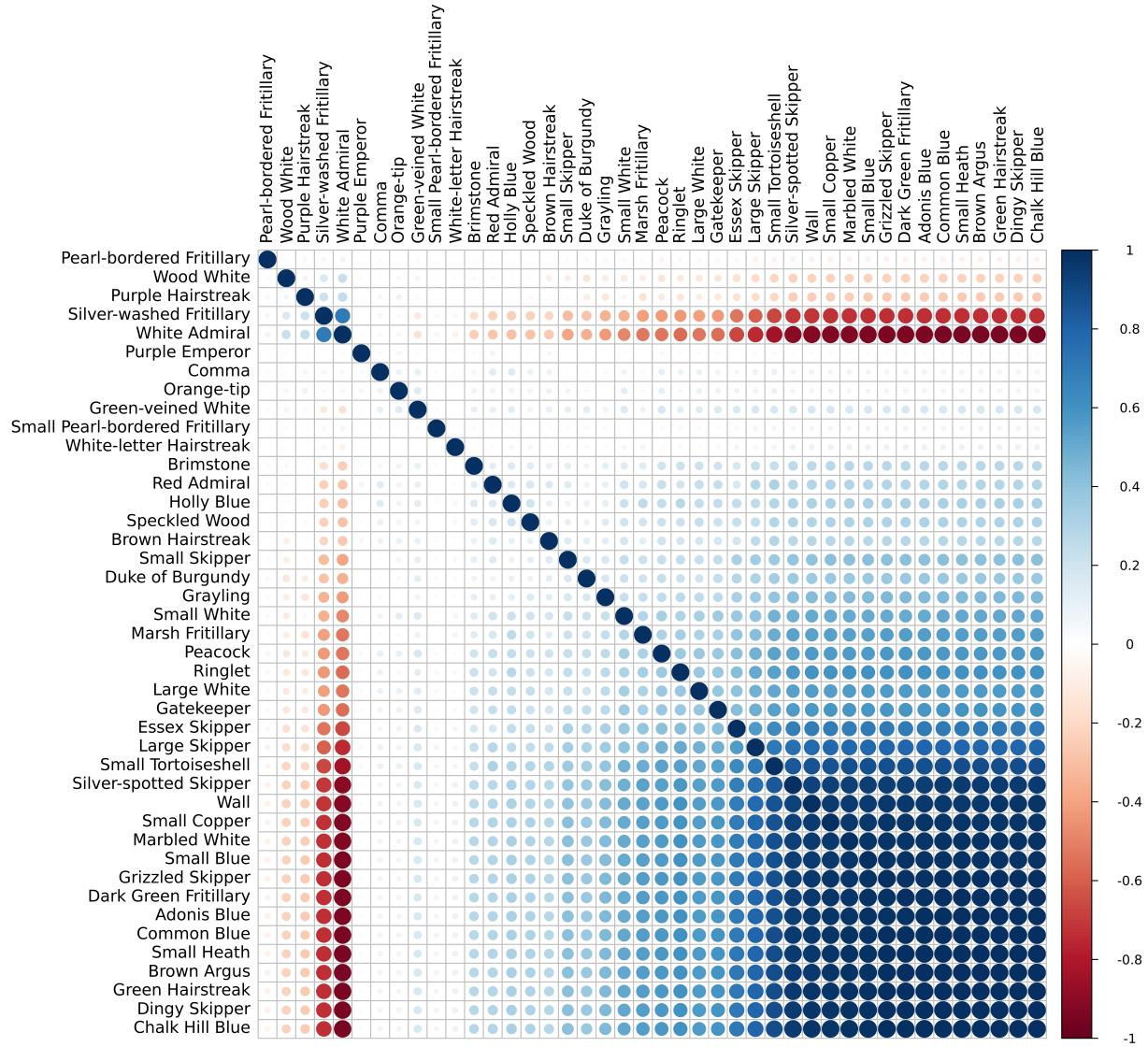


Figure 10: Fitted residual species associations defined by a correlation matrix, averaged across all time slices. Note the grouping into a large cluster dominated by chalk grassland species (bottom right) and a smaller cluster of species (top left) associated with woodlands.

Confirming Model Convergence

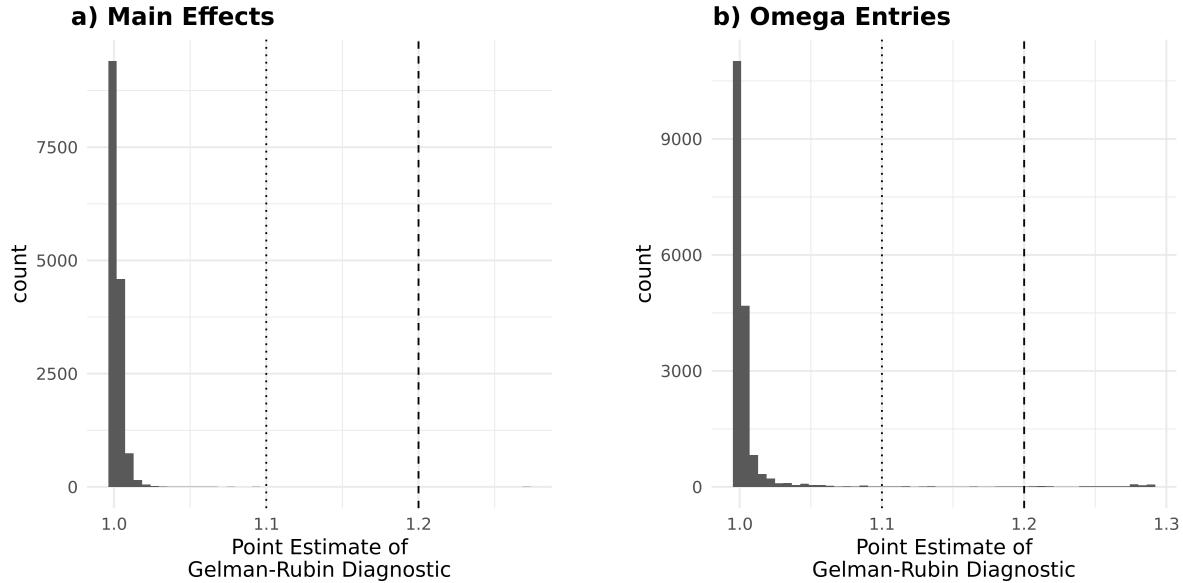


Figure 11: Histogram of Gelman-Rubin MCMC convergence statistics across all years of the butterfly dataset based on two independent chains fit for each year of the full model (total iterations = 100000, burn-in = 50000, and thinning = 50) a) Main effect coefficients (i.e. environmental and spatial coefficients) are all well below the standard threshold of 1.1, indicating acceptable convergence. b) Equivalent results for the species codistribution fitting are by necessity slightly more derived, as they are fit by latent variables that might not necessarily be fit in the same order, even if they converge. We therefore examine the convergence in the elements of the correlation matrix Ω . Here the vast majority are well converged, although there are a few correlations that exceeded 1.2. However, as these were very much a minority and were not significantly over (the maximum was 1.29), we considered these models suitable converged.

Bird Dataset

Distribution of Sites



Figure 12: Location of the hectads retained from the British Breeding Bird Atlas dataset. Boundaries (51° : 54.3° latitude, -2.3° : -0.9° longitude) were chosen to be a simple shape that excludes coastal regions. The slight shoulder is due to the non-exact alignment between the UK National Grid and lines of longitude.

Species Names

Table 2: Linnean binomials and English common names of focal bird species. “HQ” column indicates if the species had sufficient “high-quality” observations to be retained in the more restricted datasets.

Scientific Name	English Common Name	HQ
<i>Tyto alba</i>	Barn Owl	TRUE
<i>Chroicocephalus ridibundus</i>	Black-headed Gull	TRUE
<i>Lyrurus tetrix</i>	Black Grouse	FALSE
<i>Phoenicurus ochruros</i>	Black Redstart	TRUE
<i>Branta canadensis</i>	Canada Goose	TRUE
<i>Actitis hypoleucos</i>	Common Sandpiper	TRUE
<i>Sterna hirundo</i>	Common Tern	TRUE
<i>Fulica atra</i>	Coot	TRUE
<i>Emberiza calandra</i>	Corn Bunting	TRUE
<i>Numenius arquata</i>	Curlew	TRUE
<i>Cinclus cinclus</i>	Dipper	TRUE
<i>Calidris alpina</i>	Dunlin	TRUE
<i>Mareca strepera</i>	Gadwall	FALSE
<i>Spatula querquedula</i>	Garganey	TRUE
<i>Regulus regulus</i>	Goldcrest	TRUE
<i>Pluvialis apricaria</i>	Golden Plover	TRUE
<i>Accipiter gentilis</i>	Goshawk	TRUE
<i>Locustella naevia</i>	Grasshopper Warbler	TRUE
<i>Podiceps cristatus</i>	Great Crested Grebe	TRUE
<i>Picus viridis</i>	Green Woodpecker	TRUE
<i>Ardea cinerea</i>	Grey Heron	TRUE
<i>Perdix perdix</i>	Grey Partridge	TRUE
<i>Motacilla cinerea</i>	Grey Wagtail	TRUE
<i>Anser anser</i>	Greylag Goose	TRUE
<i>Coccothraustes coccothraustes</i>	Hawfinch	TRUE
<i>Circus cyaneus</i>	Hen Harrier	FALSE
<i>Falco subbuteo</i>	Hobby	TRUE
<i>Garrulus glandarius</i>	Jay	TRUE
<i>Alcedo atthis</i>	Kingfisher	TRUE
<i>Larus fuscus</i>	Lesser Black-backed Gull	FALSE
<i>Acanthis cabaret</i>	Lesser Redpoll	TRUE
<i>Dryobates minor</i>	Lesser Spotted Woodpecker	TRUE
<i>Sylvia curruca</i>	Lesser Whitethroat	TRUE
<i>Tachybaptus ruficollis</i>	Little Grebe	TRUE
<i>Charadrius dubius</i>	Little Ringed Plover	TRUE
<i>Asio otus</i>	Long-eared Owl	TRUE
<i>Poecile palustris</i>	Marsh Tit	TRUE
<i>Anthus pratensis</i>	Meadow Pipit	TRUE
<i>Falco columbarius</i>	Merlin	TRUE
<i>Cygnus olor</i>	Mute Swan	TRUE
<i>Luscinia megarhynchos</i>	Nightingale	TRUE
<i>Caprimulgus europaeus</i>	Nightjar	TRUE
<i>Sitta europaea</i>	Nuthatch	TRUE
<i>Haematopus ostralegus</i>	Oystercatcher	TRUE
<i>Ficedula hypoleuca</i>	Pied Flycatcher	TRUE

Scientific Name	English Common Name	HQ
<i>Aythya ferina</i>	Pochard	TRUE
<i>Coturnix coturnix</i>	Quail	TRUE
<i>Corvus corax</i>	Raven	FALSE
<i>Lagopus lagopus</i>	Red Grouse	TRUE
<i>Tringa totanus</i>	Redshank	TRUE
<i>Phoenicurus phoenicurus</i>	Redstart	TRUE
<i>Emberiza schoeniclus</i>	Reed Bunting	TRUE
<i>Acrocephalus scirpaceus</i>	Reed Warbler	TRUE
<i>Turdus torquatus</i>	Ring Ouzel	TRUE
<i>Charadrius hiaticula</i>	Ringed Plover	TRUE
<i>Columba livia</i>	Rock Dove	TRUE
<i>Riparia riparia</i>	Sand Martin	TRUE
<i>Acrocephalus schoenobaenus</i>	Sedge Warbler	TRUE
<i>Tadorna tadorna</i>	Shelduck	FALSE
<i>Asio flammeus</i>	Short-eared Owl	TRUE
<i>Spatula clypeata</i>	Shoveler	TRUE
<i>Spinus spinus</i>	Siskin	FALSE
<i>Gallinago gallinago</i>	Snipe	TRUE
<i>Burhinus oedicnemus</i>	Stone-curlew	TRUE
<i>Saxicola rubicola</i>	Stonechat	TRUE
<i>Anas crecca</i>	Teal	TRUE
<i>Anthus trivialis</i>	Tree Pipit	TRUE
<i>Passer montanus</i>	Tree Sparrow	TRUE
<i>Aythya fuligula</i>	Tufted Duck	TRUE
<i>Streptopelia turtur</i>	Turtle Dove	TRUE
<i>Linaria flavirostris</i>	Twite	TRUE
<i>Rallus aquaticus</i>	Water Rail	TRUE
<i>Oenanthe oenanthe</i>	Wheatear	TRUE
<i>Saxicola rubetra</i>	Whinchat	TRUE
<i>Mareca penelope</i>	Wigeon	FALSE
<i>Poecile montanus</i>	Willow Tit	TRUE
<i>Phylloscopus sibilatrix</i>	Wood Warbler	TRUE
<i>Scolopax rusticola</i>	Woodcock	TRUE
<i>Lullula arborea</i>	Woodlark	TRUE
<i>Motacilla flava</i>	Yellow Wagtail	TRUE

Species Habitat Associations

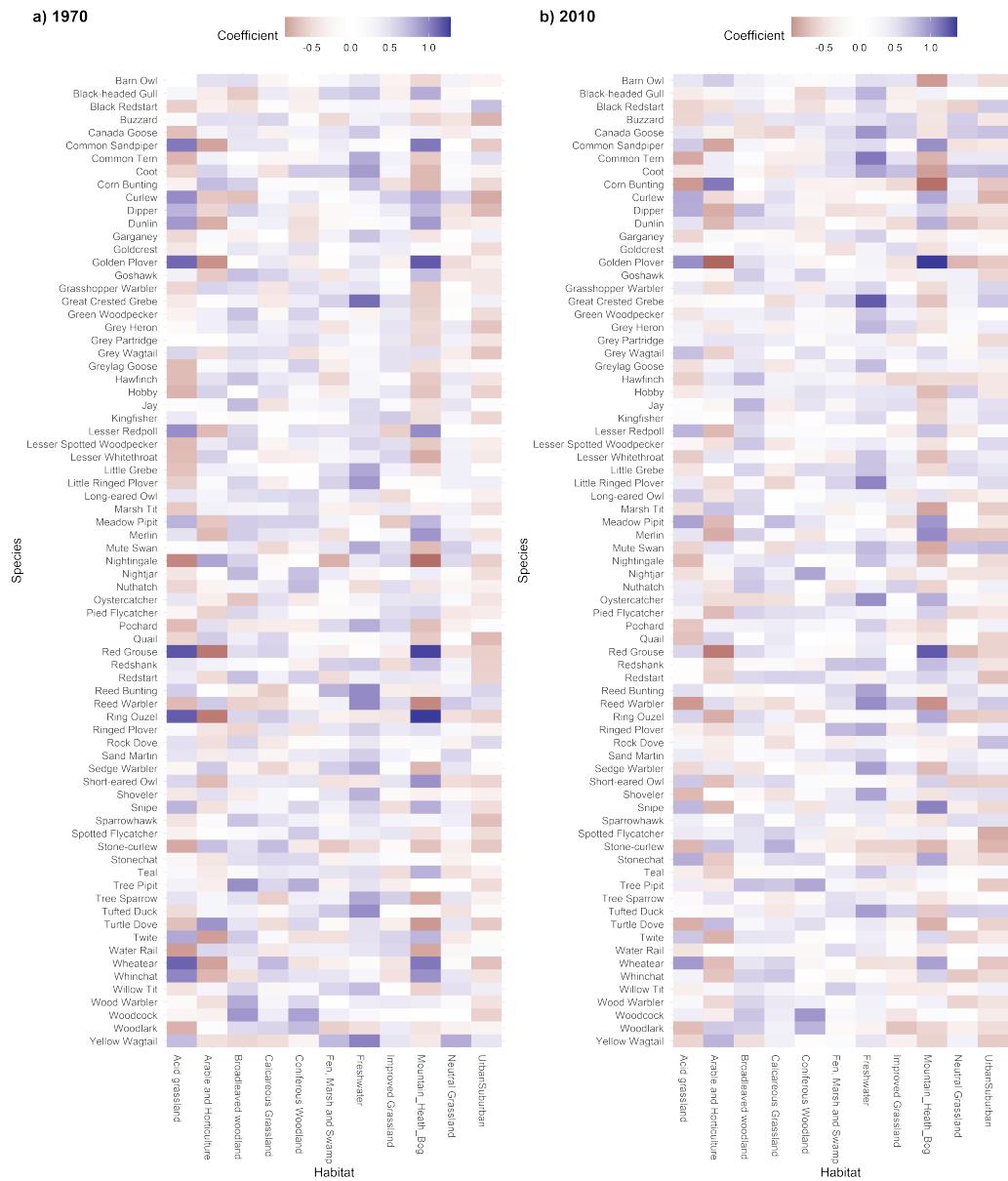


Figure 13: Fitted species-level environmental coefficients for breeding bird dataset (excluding ‘possible’ records)

Species Codistribution

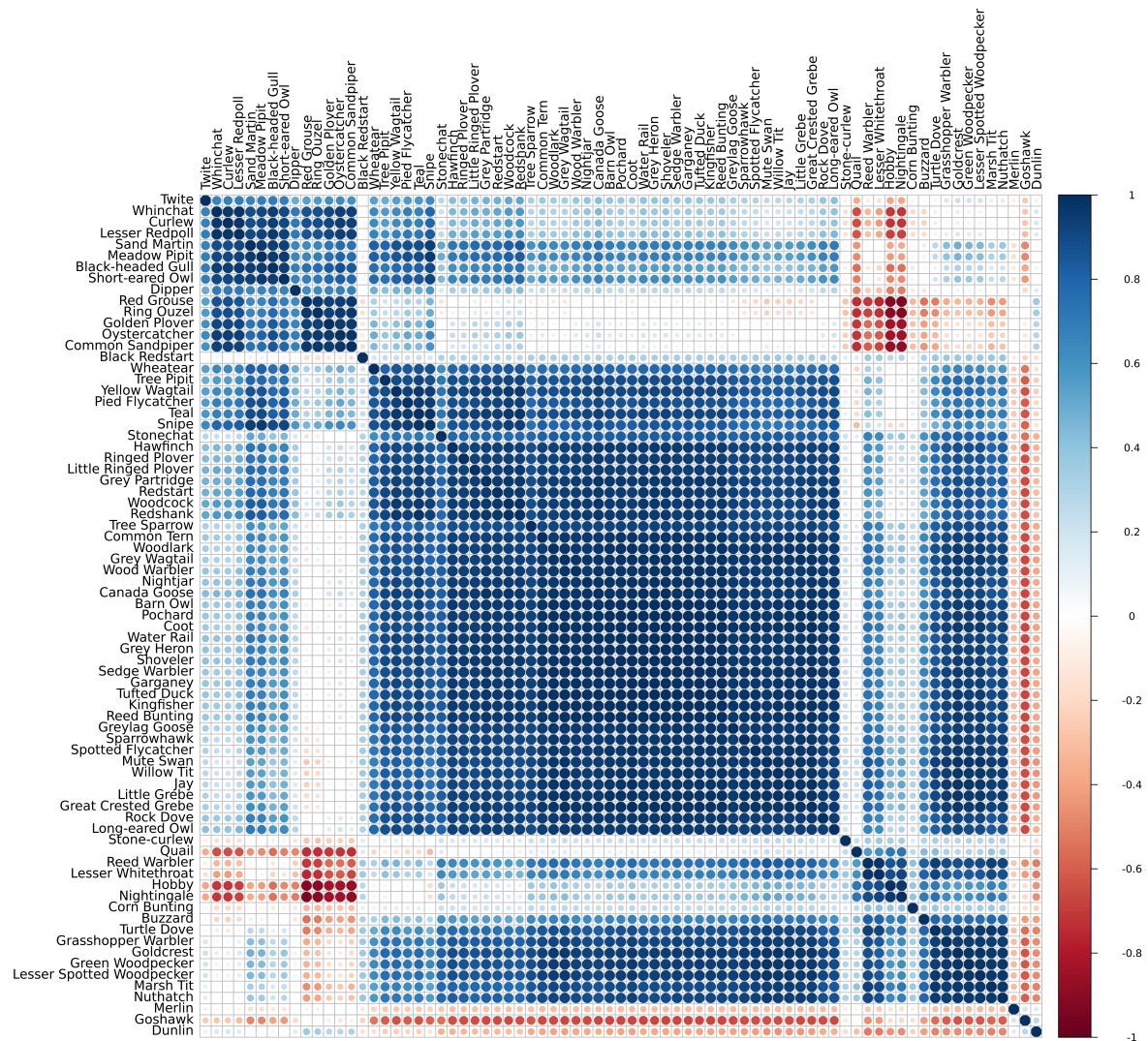


Figure 14: Fitted residual species-association matrix (correlations) for 1970 breeding bird dataset (excluding ‘possible’ records.)

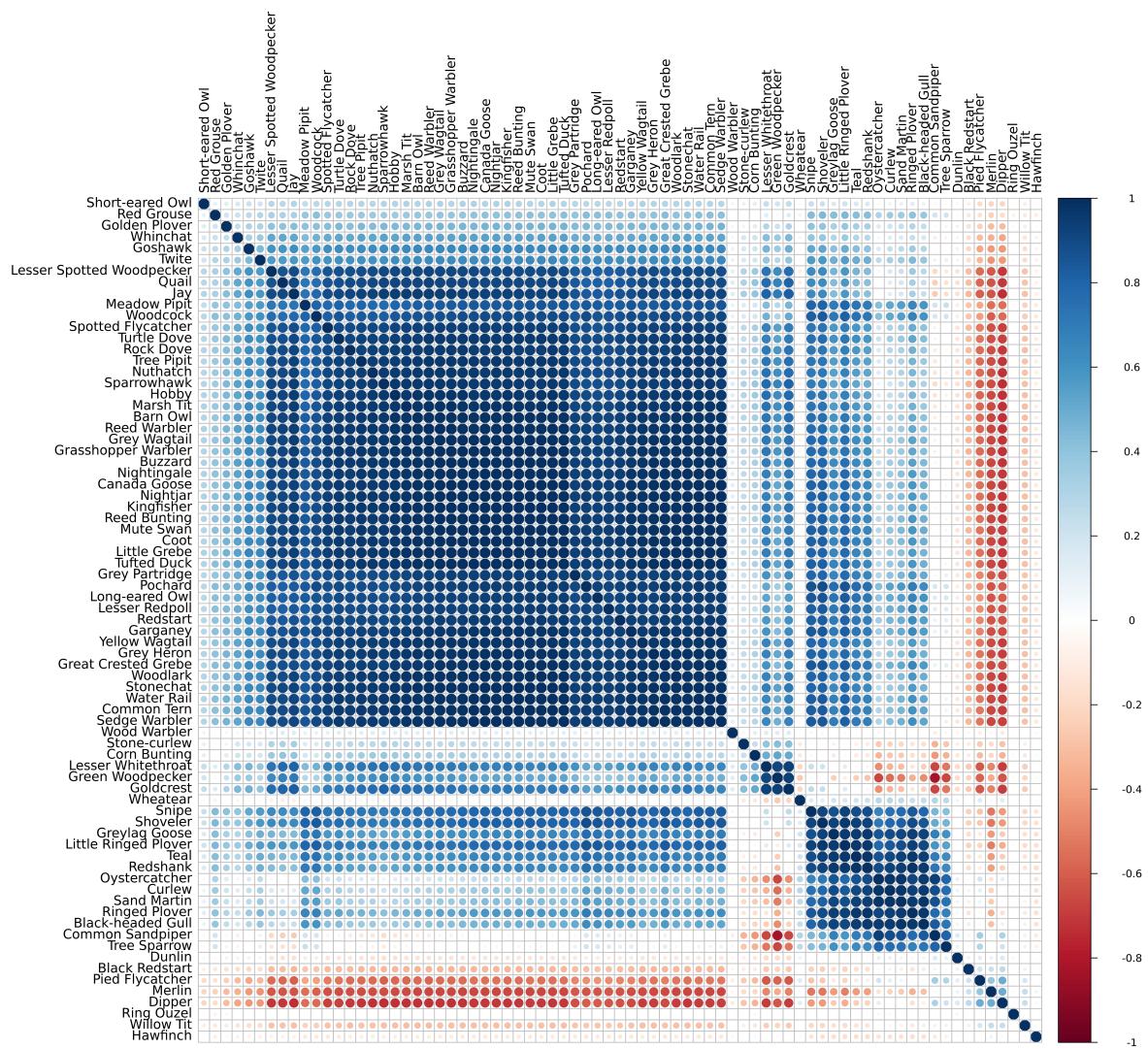


Figure 15: Fitted residual species-association matrix (correlations) for 2010 breeding bird dataset (excluding ‘possible’ records.)

MCMC Convergence

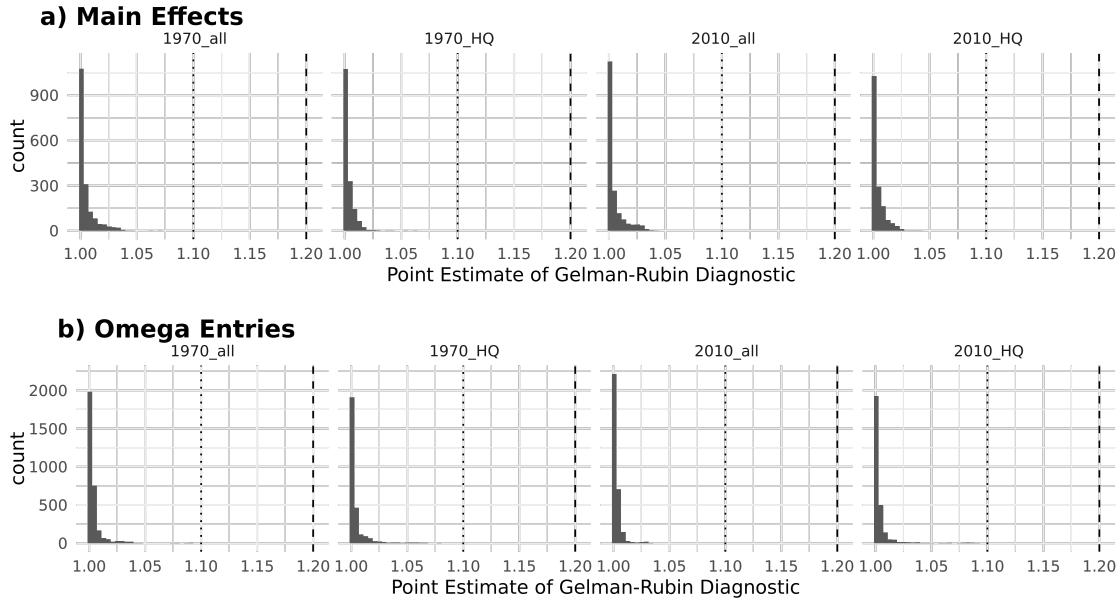


Figure 16: Distribution of Gelman-Rubin MCMC convergence diagnostic value point estimates for the bird datasets, calculated from 4 independent MCMC chains of the ‘full’ model. Values are faceted by year and whether all data is used, or excluding ‘possible’ observations (HQ). a) Main effect coefficients (i.e. environmental and spatial variables). Largest value was 1.069. b) Elements of the correlation matrix (Ω). Largest value was 1.102. All were well below the standard thresholds indicating convergence is likely achieved.