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

Authorship Redacted for blind review

Contents

Simulations

Simulation Setup Example

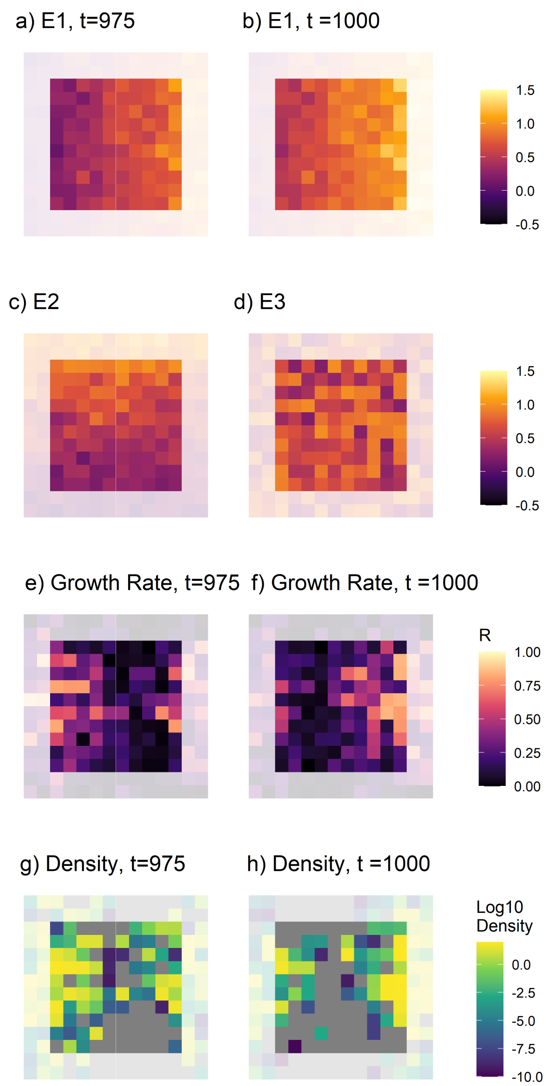

Figure 1: Example illustration of the simulation model, focussing on an single species. Values are drawn from the same simulation as illustrated in the main text Figure 2. Values from the peripheral sites not used for the JSDM fitting are shown greyed out. a) Pre-change distribution of E_1 variable. This variable increases through time, and could be considered 'temperature'. b) E_1 variable at $t = 1000$. c)Distribution of E_2. This variable is fixed throughout the simulation and so could be considered an aspect of geology. d) Distribution of 'idiosynctratic 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. e) Growth rate R, of an example species before the onset of climate change. Note the approximately circular shape, but the high degree of heterogeneity. f) 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. g) Pre-climate change distribution of an example species. Note the approximate correspondence with the growth rates, but also infilling due to dispersal mass-effects h) 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 (f).

Impact of parameters on metacommunity size and occupancy

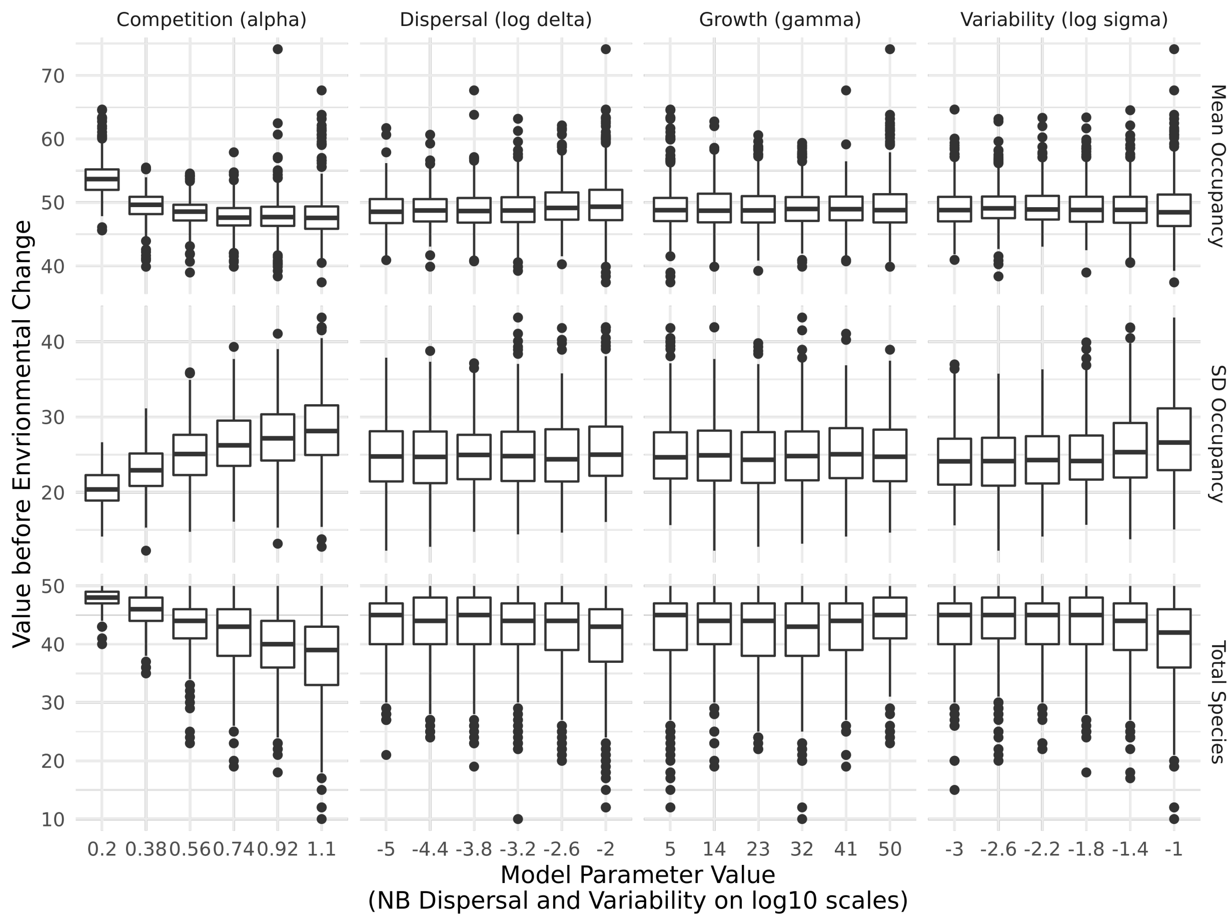

Figure 2: Impact of simulation model parameters on key metacommunity statistics prior to the introduction of environmental change. Only species that are used in the JSDMs are included here, i.e. excluding those that are too rare (or abundant) within the focal squares. Each facet includes all 2460 simulations, 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

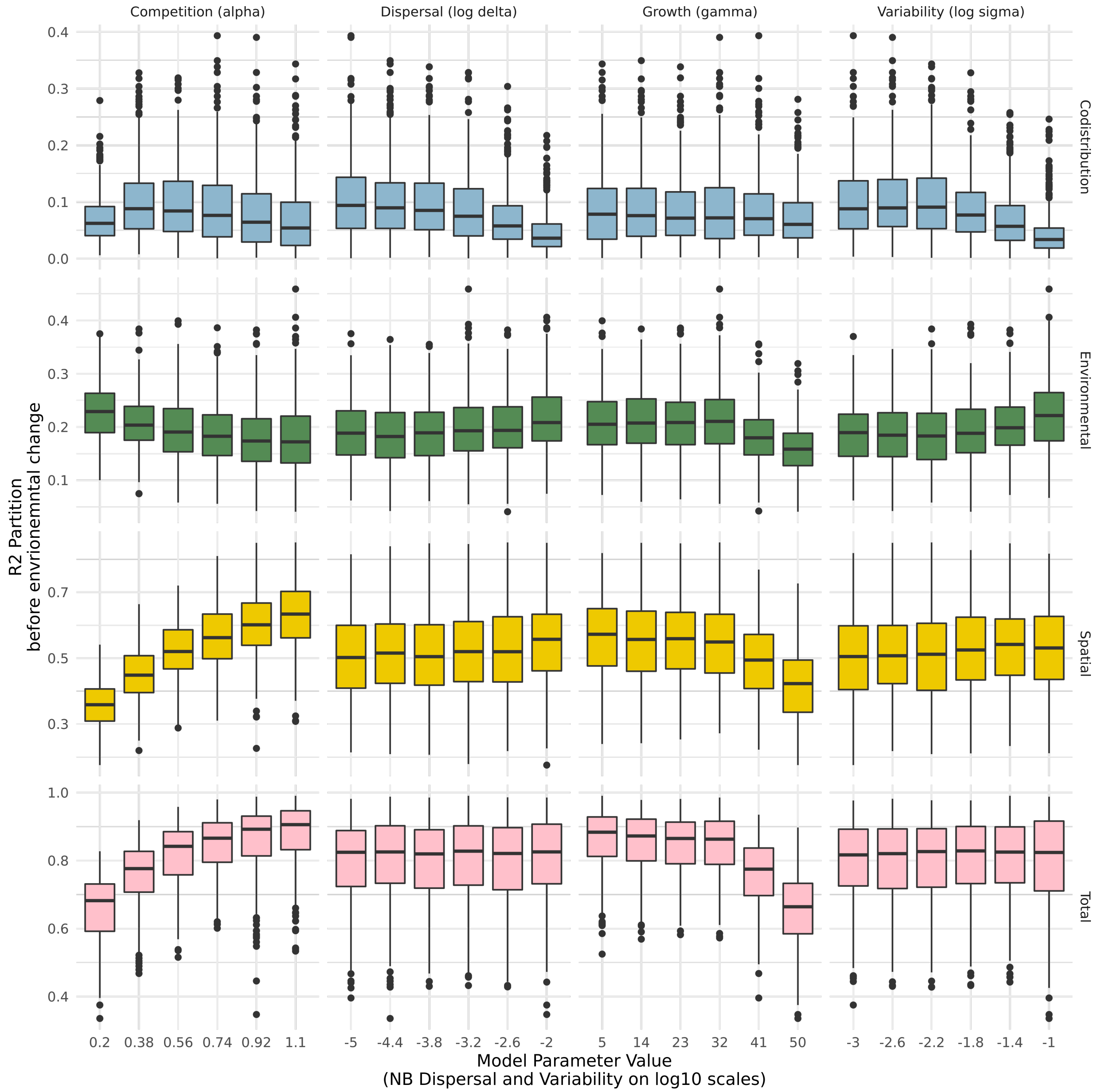

Figure 3: Impact of the model parameters on the simulated metacommunity structure, as assessed by variance partitioning before the introduction of environmental change. Boxplots hinges show 25 and 75th percentiles.

Impact of parameters on shift in simulated metacommunity structure

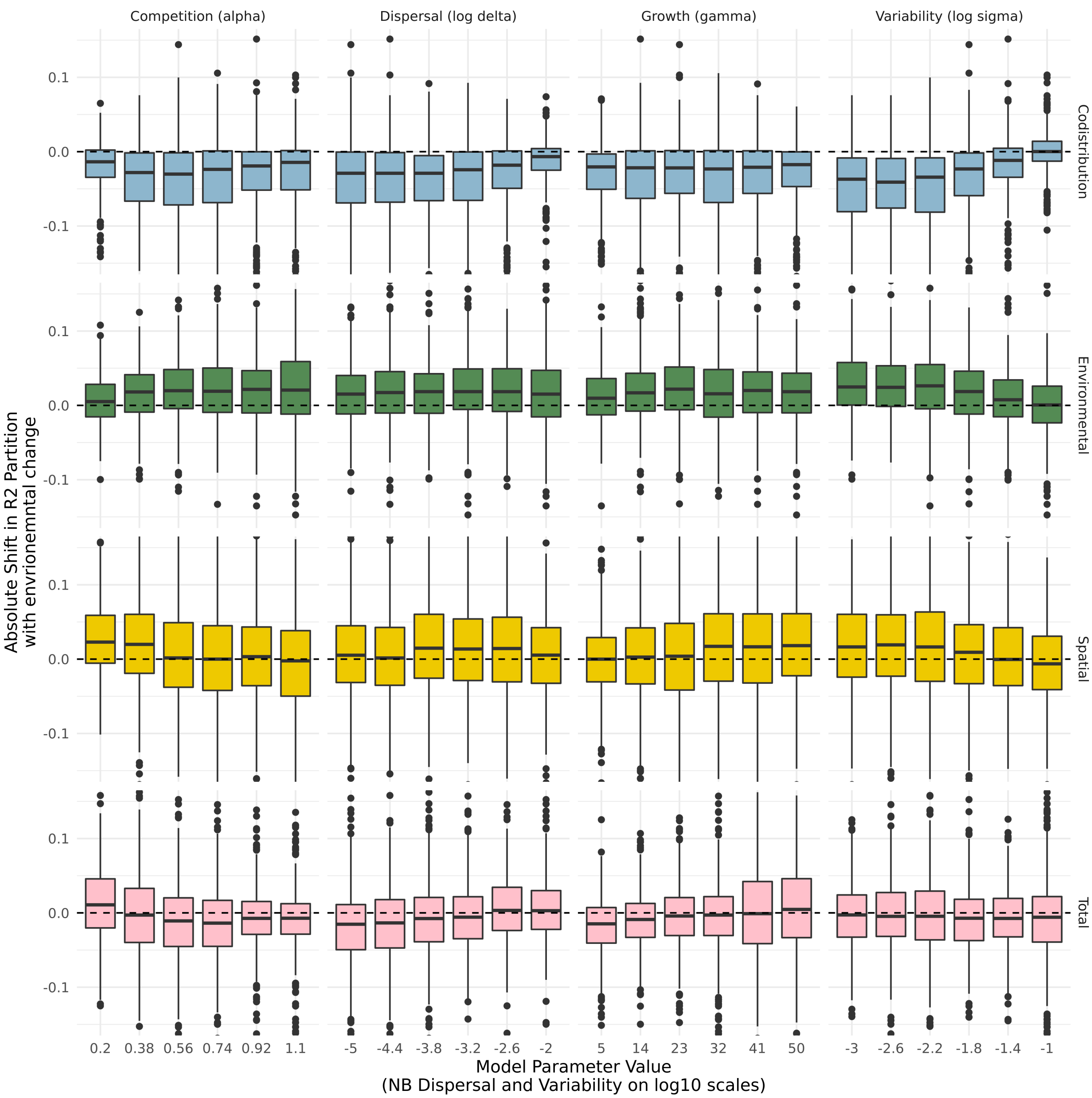

Figure 4: The dependence of shifts in the variance partitioning on the parameters of the simulated metacommunities. Figure 3 in the main text is a summary of this plot. Boxplots hinges show 25 and 75th percentiles.

Impact of false absences on detectability of shift in metacommunity structure

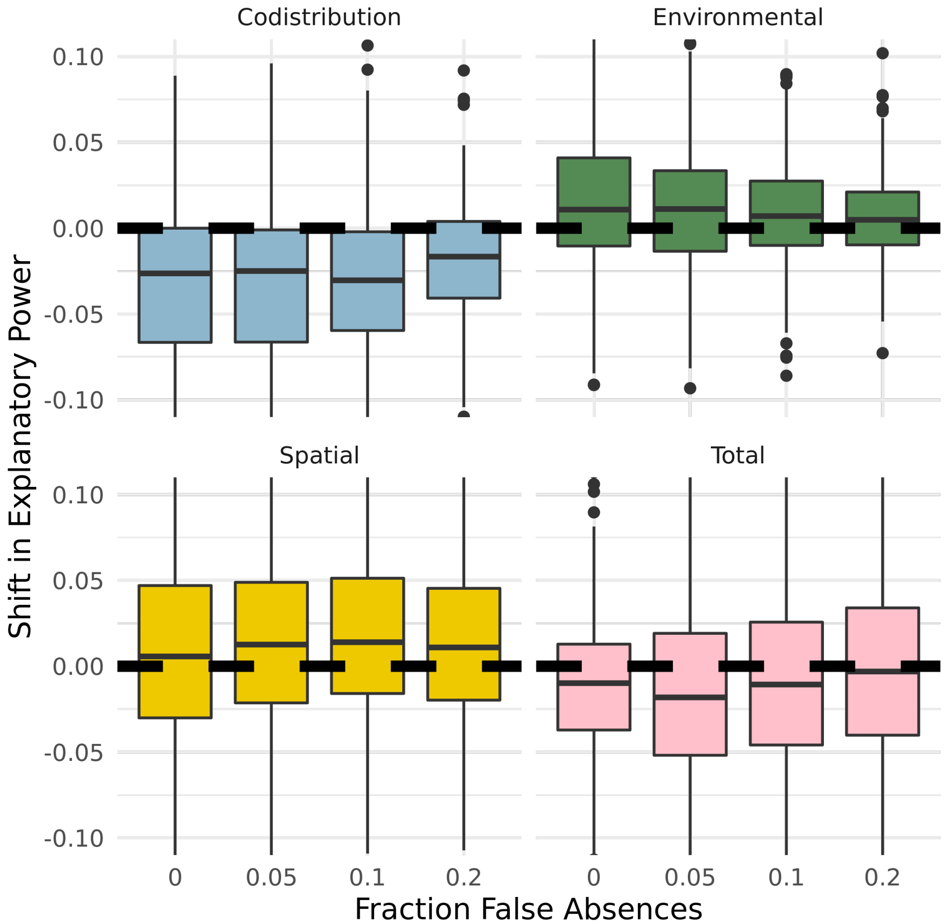

Figure 5: Impact of false absences on the consistent identity of trends. Simulation was run as with the analysis in the main text, but with a reduced spread of core model parameters (δ: $10^{-5}, 10^{-4}, 10^{-3}$; α; $0.3, 0.8, 1.1$, γ: $5, 20, 40$, σ: $10^{-3}, 10^{-2}, 10^{-1}$), crossed with 4 levels 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

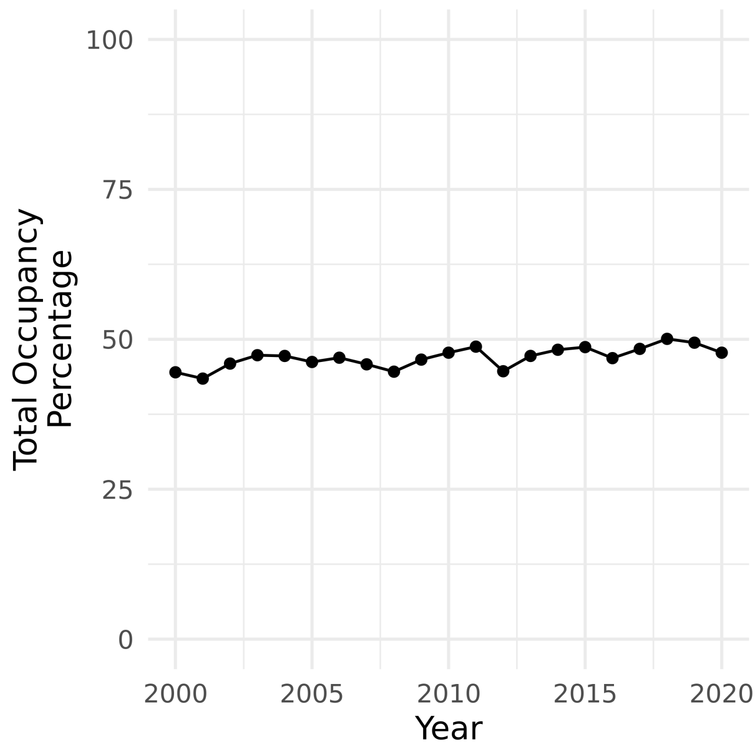

Figure 7: Total occupancy (i.e. total species:site presence records out of maximum possible) of focal butterfly species in focal sites across the time period.

Species-Level Responses

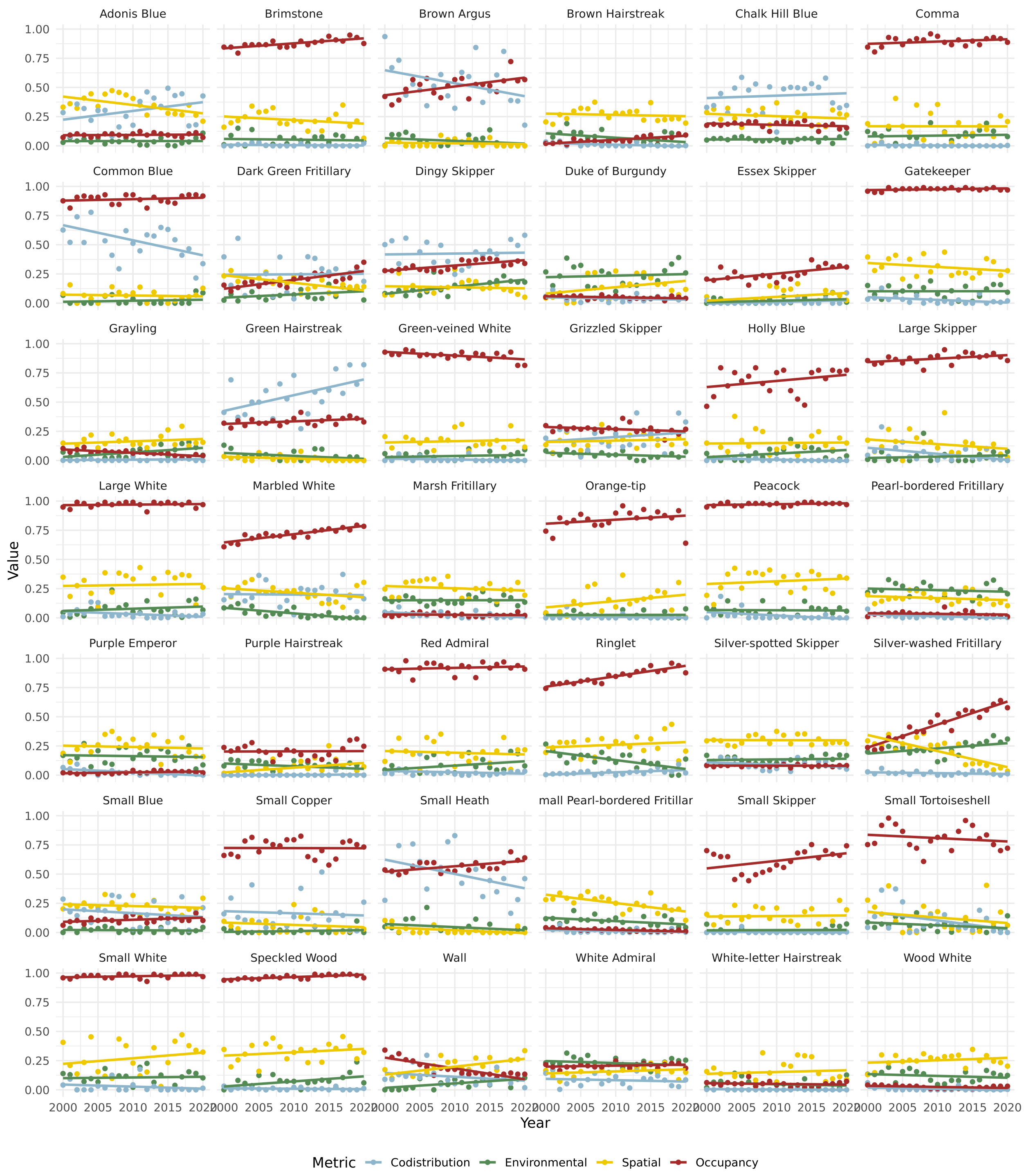

Figure 8: Species-level variance partitioning and species occupancy fraction (out of the 97 focal sites) through time. Note that the changes in the overall variance partitioning are driven by changes in relatively few of the species. However, these species (for example Common Blue and Green Hairstreak) 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
Polyommatus bellargus	Adonis Blue
Gonepteryx rhamni	Brimstone
Aricia agestis	Brown Argus
Thecla betulae	Brown Hairstreak
Polyommatus coridon	Chalk Hill Blue
Polygonia c-album	Comma
Polyommatus icarus	Common Blue
Speyeria aglaja	Dark Green Fritillary
Erynnis tages	Dingy Skipper
Hamearis lucina	Duke of Burgundy
Thymelicus lineola	Essex Skipper
Pyronia tithonus	Gatekeeper
Hipparchia semele	Grayling
Pieris napi	Green-veined White
Callophrys rubi	Green Hairstreak
Pyrgus malvae	Grizzled Skipper
Celastrina argiolus	Holly Blue
Ochlodes sylvanus	Large Skipper
Pieris brassicae	Large White
Melanargia galathea	Marbled White
Euphydryas aurinia	Marsh Fritillary
Anthocharis cardamines	Orange-tip
Aglais io	Peacock
Boloria euphrosyne	Pearl-bordered Fritillary
Apatura iris	Purple Emperor
Favonius quercus	Purple Hairstreak
Vanessa atalanta	Red Admiral
Aphantopus hyperantus	Ringlet
Hesperia comma	Silver-spotted Skipper
Argynnis paphia	Silver-washed Fritillary
Cupido minimus	Small Blue
Lycaena phlaeas	Small Copper
Coenonympha pamphilus	Small Heath
Boloria selene	Small Pearl-bordered Fritillary
Thymelicus sylvestris	Small Skipper
Aglais urticae	Small Tortoiseshell
Pieris rapae	Small White
Pararge aegeria	Speckled Wood
Lasiommata megera	Wall
Satyrium w-album	White-letter Hairstreak
Limenitis camilla	White Admiral
Leptidea sinapis	Wood White

Fitted Environmental Coefficients

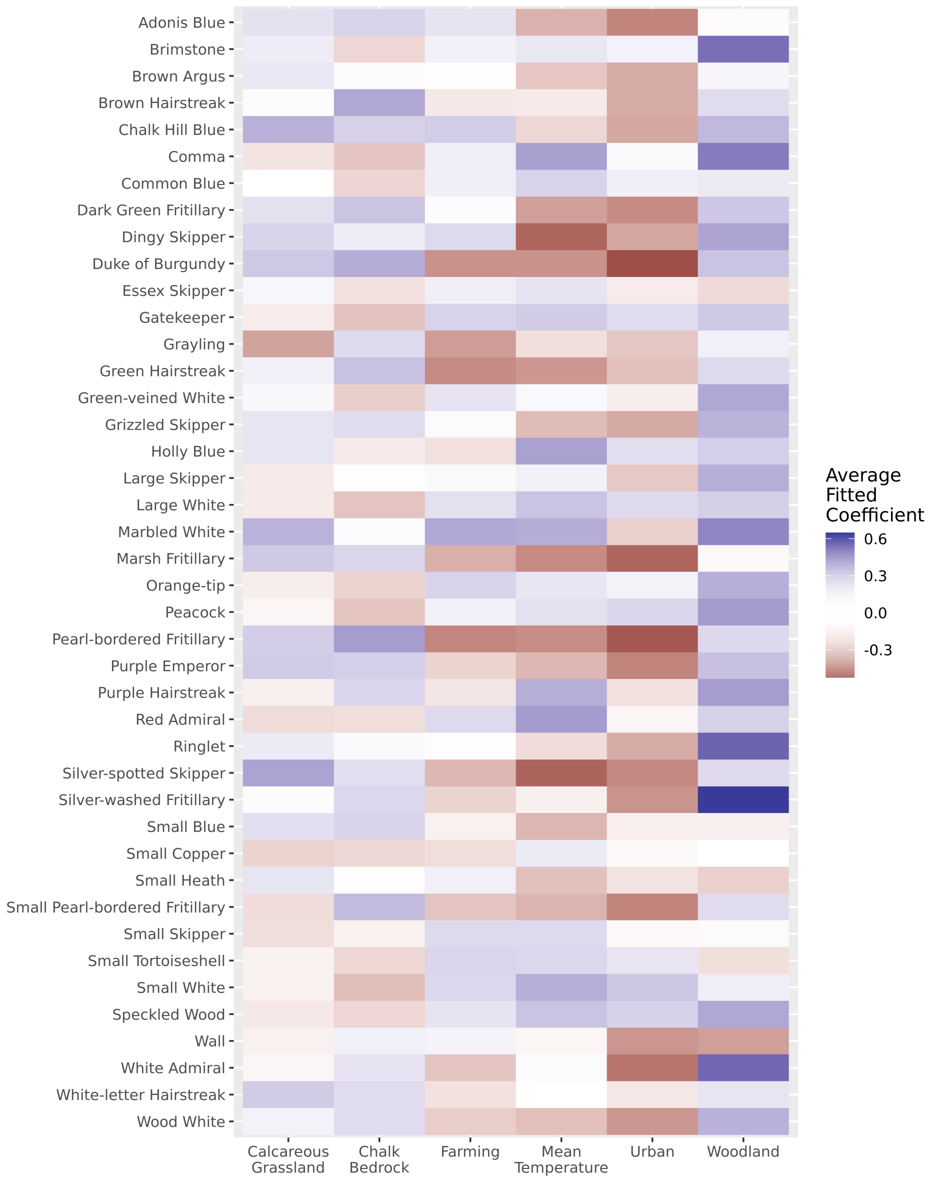

Figure 9: Butterfly fitted species-level environmental coefficients, averaged across all 21 years.

Fitted Species Associations

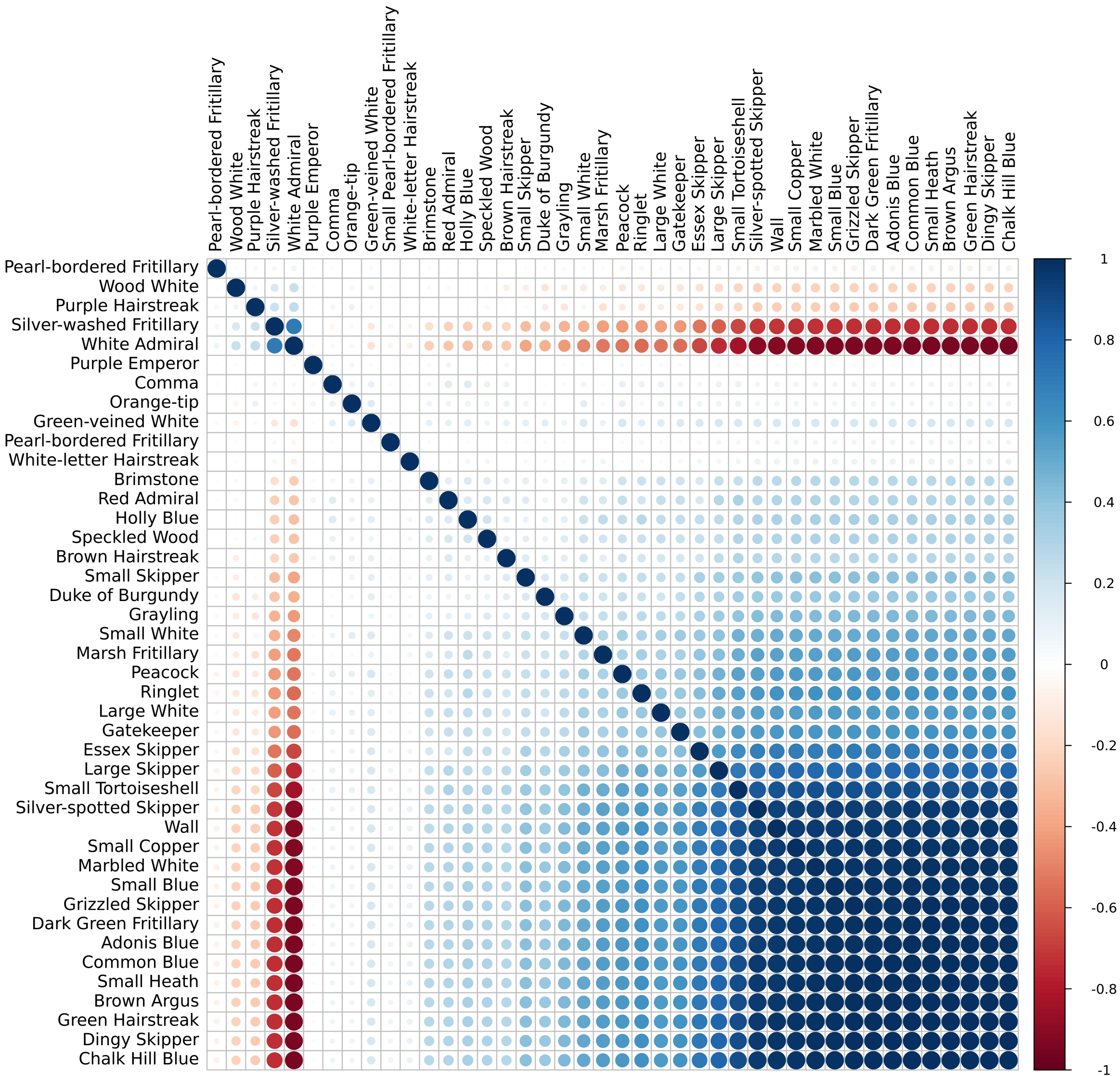

Figure 10: Fitted residual species associations defined by a correlation matrix, averaged across all time slices. Note the grouping into a large cluster dominated by chalk grassland species (bottom right) and a smaller cluster of species (top left) associated with woodlands.

Confirming Model Convergence

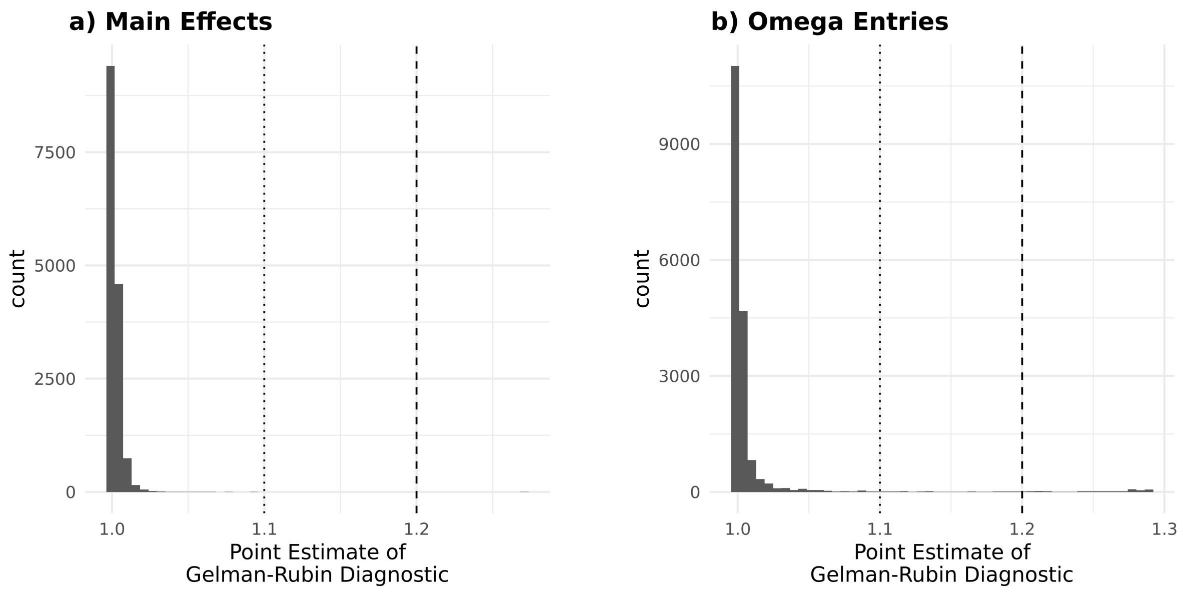

Figure 11: Histogram of Gelman-Rubin MCMC convergence statistics across all years of the butterfly dataset based on two independent chains fit for each year of the full model (total iterations = 100000, burn-in = 50000, and thinning = 50) a) Main effect coefficients (i.e. environmental and spatial coefficients) 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 signifcantly 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
Tyto alba	Barn Owl	TRUE
Chroicocephalus ridibundus	Black-headed Gull	TRUE
Lyrurus tetrix	Black Grouse	FALSE
Phoenicurus ochruros	Black Redstart	TRUE
Branta canadensis	Canada Goose	TRUE
Actitis hypoleucos	Common Sandpiper	TRUE
Sterna hirundo	Common Tern	TRUE
Fulica atra	Coot	TRUE
Emberiza calandra	Corn Bunting	TRUE
Numenius arquata	Curlew	TRUE
Cinclus cinclus	Dipper	TRUE
Calidris alpina	Dunlin	TRUE
Mareca strepera	Gadwall	FALSE
Spatula querquedula	Garganey	TRUE
Regulus regulus	Goldcrest	TRUE
Pluvialis apricaria	Golden Plover	TRUE
Accipiter gentilis	Goshawk	TRUE
Locustella naevia	Grasshopper Warbler	TRUE
Podiceps cristatus	Great Crested Grebe	TRUE
Picus viridis	Green Woodpecker	TRUE
Ardea cinerea	Grey Heron	TRUE
Perdix perdix	Grey Partridge	TRUE
Motacilla cinerea	Grey Wagtail	TRUE
Anser anser	Greylag Goose	TRUE
Coccothraustes coccothraustes	Hawfinch	TRUE
Circus cyaneus	Hen Harrier	FALSE
Falco subbuteo	Hobby	TRUE
Garrulus glandarius	Jay	TRUE
Alcedo atthis	Kingfisher	TRUE
Larus fuscus	Lesser Black-backed Gull	FALSE
Acanthis cabaret	Lesser Redpoll	TRUE
Dryobates minor	Lesser Spotted Woodpecker	TRUE
Sylvia curruca	Lesser Whitethroat	TRUE
Tachybaptus ruficollis	Little Grebe	TRUE
Charadrius dubius	Little Ringed Plover	TRUE
Asio otus	Long-eared Owl	TRUE
Poecile palustris	Marsh Tit	TRUE
Anthus pratensis	Meadow Pipit	TRUE
Falco columbarius	Merlin	TRUE
Cygnus olor	Mute Swan	TRUE
Luscinia megarhynchos	Nightingale	TRUE
Caprimulgus europaeus	Nightjar	TRUE
Sitta europaea	Nuthatch	TRUE
Haematopus ostralegus	Oystercatcher	TRUE
Ficedula hypoleuca	Pied Flycatcher	TRUE

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

Species Habitat Associations

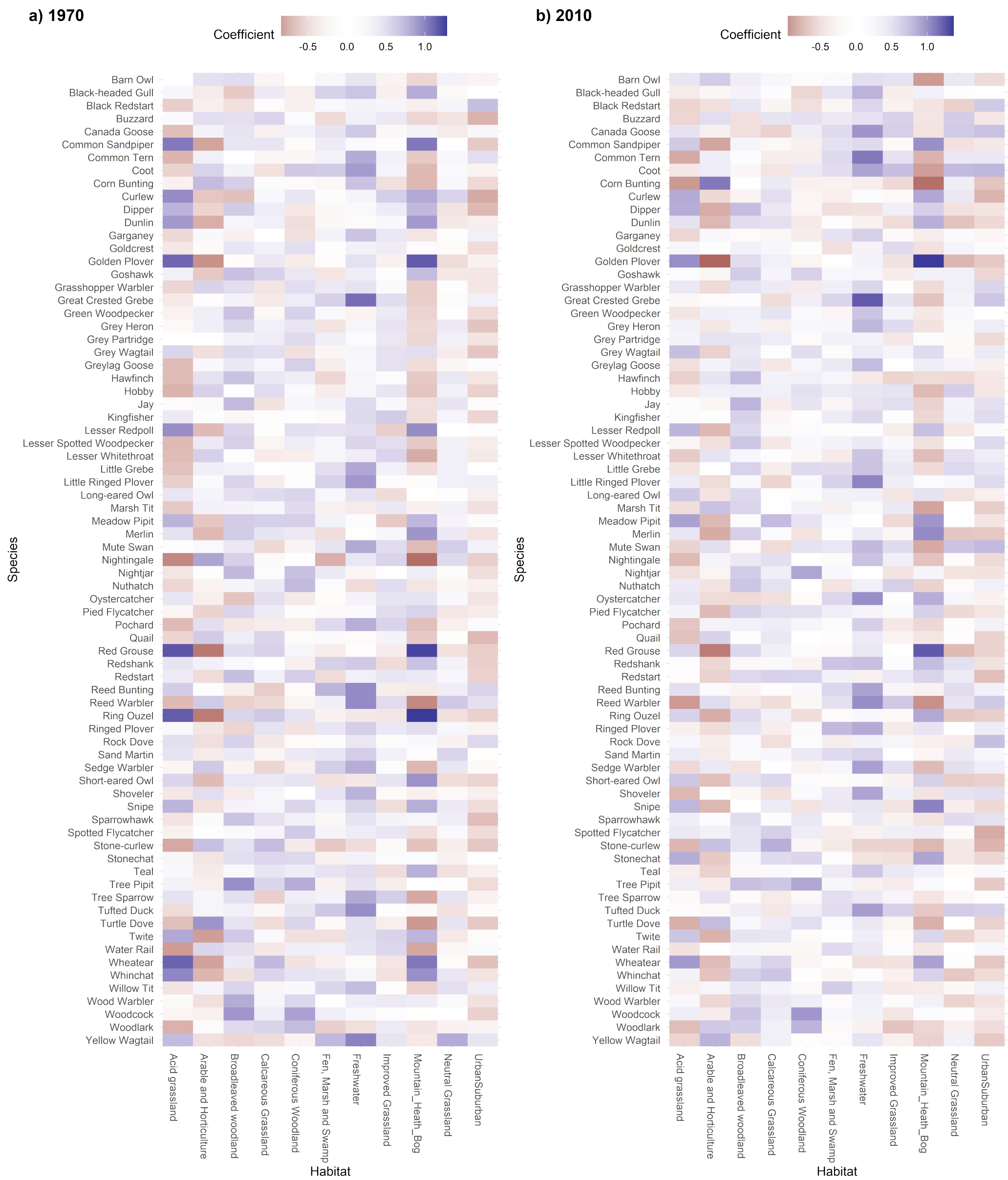

Figure 13: Fitted species-level environmental coefficients for breeding bird dataset (excluding 'possible' records)

Species Codistribution

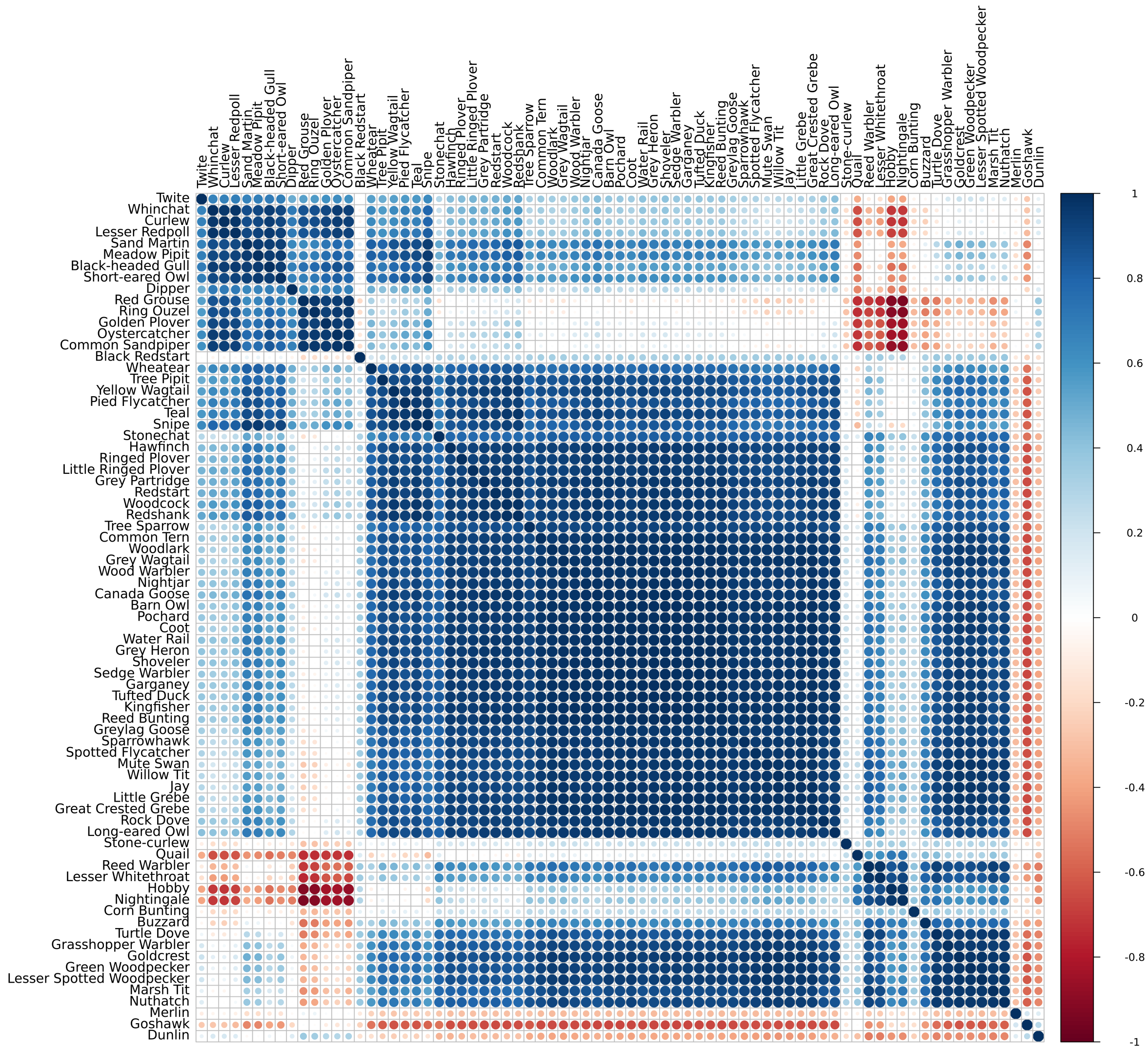

Figure 14: Fitted residual species-association matrix (correlations) for 1970 breeding bird dataset (excluding ‘possible’ records.)

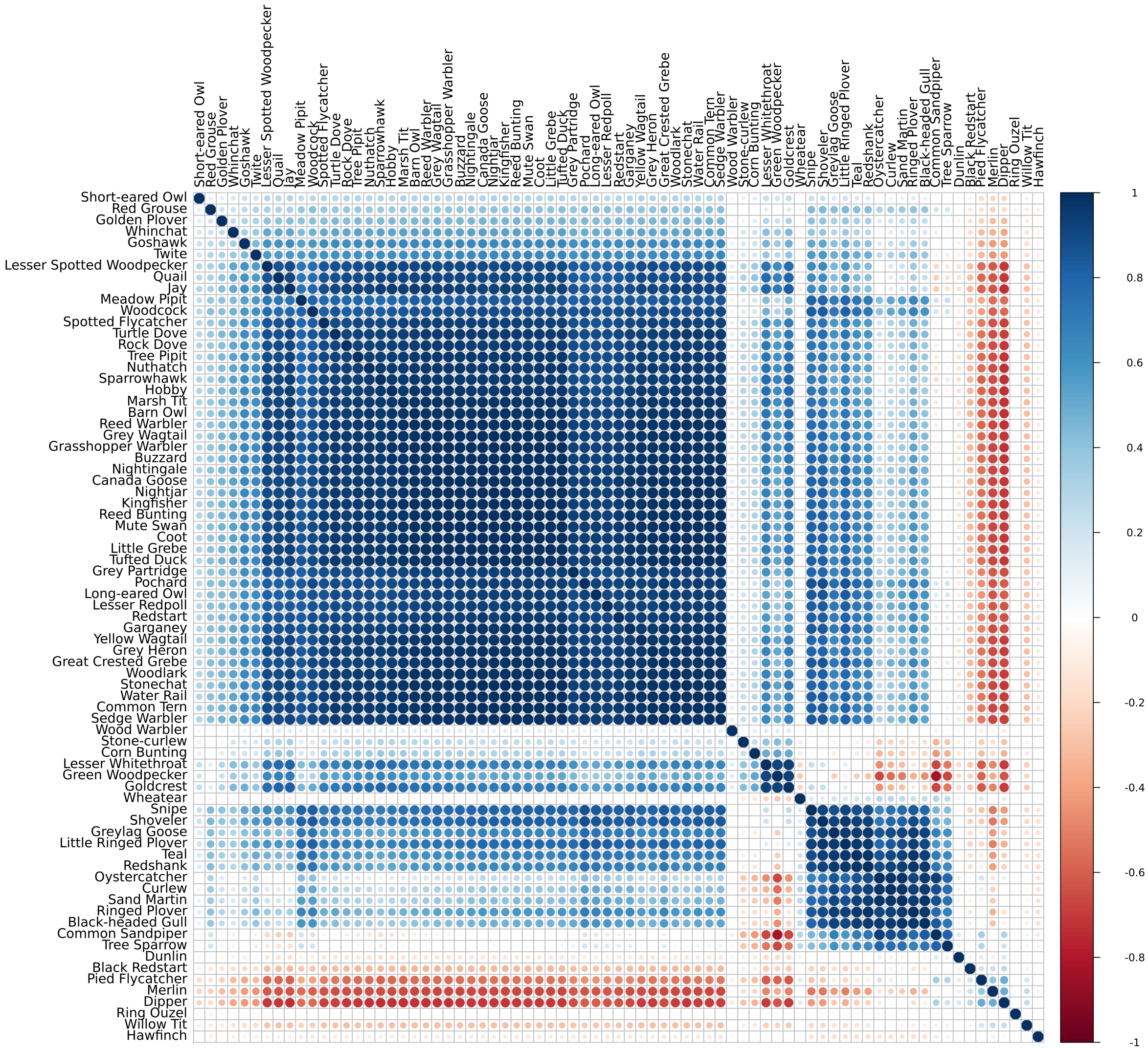

Figure 15: Fitted residual species-association matrix (correlations) for 2010 breeding bird dataset (excluding ‘possible’ records.)

MCMC Convergence

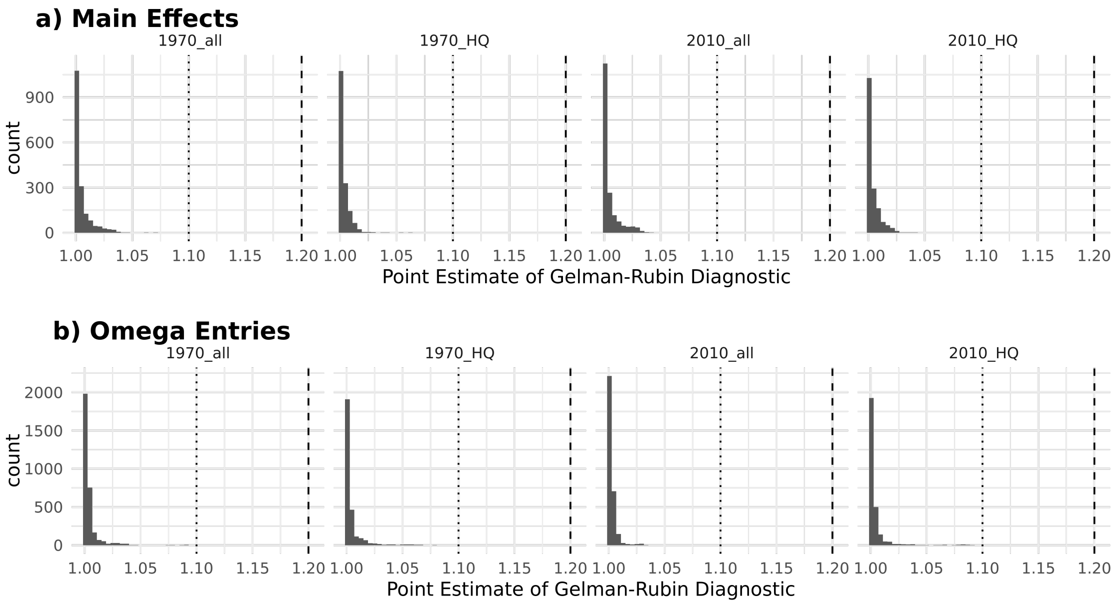

Figure 16: Distribution of Gelman-Rubin MCMC convergence diagnostic value point estimates for the bird datasets, calculated from 4 independent MCMC chains of the 'full' model. Values are faceted by year and whether all data is used, or excluding 'possible' observations (HQ). a) Main effect coefficients (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.