Supplementary Information and Results

Testing the socio-economic and environmental determinants of better child-health outcomes in Africa: a cross-sectional study among nations

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Table S1. Studies highlighting the relationships between different child-health indicators (response) and environmental and socio-economic correlates at different spatial scales cited in the main text.

Child-health indicator (response)	Correlate(s)	Spatial scale	Reference
child growth failure (wasting, stunting, underweight)	none (only spatial-temporal trends reported)	5 × 5 km gridded estimate across 51 sub-Saharan countries	1
infant mortality	air quality ($PM_{2.5}$ μm exposure)	0.01 × 0.01° gridded estimate across 30 sub-Saharan countries	2
child mortality (< 5 years)	local temperature, malaria burden, recent history of conflict	0.01 × 0.01° gridded estimate across 28 sub-Saharan countries	3
chronic undernutrition	educational attainment of mothers, food production, improved water & sanitation	Burkina Faso (community-level; clusters of households)	4
child wasting, stunting, underweight	household size (dependency, nucleation)	Ghana (household level)	5
child mortality	population density	Zimbabwe (regional)	6
infant & child mortality	use of non-solid cooking fuel, use of improved sanitation & water	15 sub-Saharan countries (national)	7
child (< 5 years) mortality	air quality ($PM_{2.5}$ μm concentrations), urban population size, proportion of population employed, tuberculosis death rate	0.01 × 0.01° gridded estimate across 54 African countries	8
infant mortality & height-for-age	population density, prevalence of open defecation, access to sanitation	global (country & regional scale)	9
infant & child mortality	globalization, democracy, GDP	70 developing countries (national)	10
child weight-for-height & height-for-age, incidence of diarrhoea	rainfall shocks	Nigeria (community clusters)	11
infant & child mortality	immunization, use of bed nets, economic growth	Tanzania (regional)	12

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Structural equation models

We constructed seventeen candidate models (Table S2) to examine the socio-economic and environmental correlates of child health among African countries, keeping the hypothesised relationships between potentially explanatory variables constant in all. These were: (a) a one-way correlation between mean household size and governance, assuming that higher household densities (as a proxy for population density) potentially affect governance quality[13]; (b) a one-way correlation between mean household size and environmental performance because population density is correlated with environmental performance[14]; (c) a one-way correlation between per-capita GDP and health investment, assuming that wealthier nations invest proportionally more into their health-delivery systems; (d) a one-way correlation between environmental performance and food supply, assuming that degraded environments at least at some point affect food availability or quality for its citizens[15-19]; and (e) a one-way correlation between environmental performance and improved water/sanitation availability. We fitted the candidate path models to the data using the `sem` function[20] implemented in the R Package[21], calculating Bayesian information criterion (BIC) weights to assign relative strength of evidence to each model in the set. We evaluated the goodness-of-fit of each model using McDonald's non-centrality index [22] and Bollen's incremental fit index[23] using the `semGOF` library in R, both of which should be > 0.90 to consider a model's fit to be acceptable[23]. We also considered structural equation models using single environmental indicators to examine which elements of environmental change were most influenced by variation in socio-economic conditions.

According to the seventeen structural equation models for the composite child-health index (Table S2), the strongest predictors (i.e., appearing the most often in highest-ranked and highest goodness-of-fit models) of the composite child-health index among African countries were wealth (per capita GDP), governance quality, access to improved water/sanitation, and environmental performance (Table S2), such that child health improved as a country's wealth, governance, access to improved water/sanitation, and environmental performance increased (Fig. 2B,C,E,H). However, none of the models had sufficient goodness of fit (McDonald's non-centrality index [22] and Bollen's incremental fit index[23] both < 0.9), which is probably a function of inadequate sample size (number of countries)[24].

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Table S2. Structural equation models considered in the model set correlating socio-economic and environmental variables to the composite child-health index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
GDP+GOV	37	135.382	-	0.643	0.274	0.541
H2O	38	141.063	2.044	0.231	0.258	0.517
GDP	38	144.229	5.210	0.048	0.247	0.502
ENV+H2O	37	140.757	5.375	0.044	0.255	0.516
ENV+HS+H2O	36	138.784	7.040	0.019	0.259	0.523
GDP+HINV	37	143.657	8.276	0.010	0.246	0.503
HINV	38	149.505	10.486	0.003	0.231	0.478
ALL	30	122.232	12.314	0.001	0.297	0.584
GOV	38	156.323	17.304	<0.001	0.211	0.446
ENV+PM25	37	155.987	20.605	<0.001	0.209	0.445
FOOD	38	160.448	21.429	<0.001	0.200	0.426
PM25	38	161.691	22.672	<0.001	0.196	0.421
FOOD+BF	37	159.385	24.003	<0.001	0.200	0.429
ENV+HS	37	160.297	24.915	<0.001	0.197	0.425
HS	38	164.340	25.321	<0.001	0.190	0.408

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

We also repeated the structural equation models for each individual health metric (Tables S3-S7):

Table S3. Structural equation models considered in the model set correlating socio-economic and environmental variables to the **stunting** index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
GDP	38	134.719	-	0.440	0.280	0.526
GDP+GOV	37	131.615	0.533	0.337	0.288	0.538
GDP+HINV	37	134.242	3.160	0.091	0.278	0.525
FOOD	38	139.259	4.540	0.045	0.264	0.503
H2O	38	139.510	4.791	0.040	0.263	0.502
ENV+H2O	37	136.334	5.253	0.032	0.271	0.515
FOOD+BF	37	139.177	8.096	0.008	0.261	0.501
ENV+HS+H2O	36	136.276	8.832	0.005	0.267	0.513
HINV	38	146.109	11.390	0.001	0.241	0.470
ALL	30	122.183	16.564	<0.001	0.297	0.565
ENV	38	152.300	17.581	<0.001	0.222	0.439
ENV+HS	37	151.517	20.435	<0.001	0.222	0.441
ENV+PM25	37	151.964	20.883	<0.001	0.220	0.439
GOV	38	155.633	20.914	<0.001	0.213	0.423
BF	38	157.570	22.851	<0.001	0.207	0.414
HS	38	158.734	24.015	<0.001	0.204	0.408
PM25	38	159.201	24.482	<0.001	0.203	0.406

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Table S4. Structural equation models considered in the model set correlating socio-economic and environmental variables to the **respiratory infection** index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
ALL	30	123.440	-	0.946	0.292	0.596
H2O	38	159.699	7.158	0.026	0.202	0.456
GDP+GOV	37	158.462	9.558	0.008	0.202	0.459
FOOD+BF	37	158.824	9.920	0.007	0.201	0.457
ENV+H2O	37	159.161	10.258	0.006	0.200	0.456
ENV+HS+H2O	36	157.115	11.849	0.003	0.203	0.463
GOV	38	165.020	12.479	0.002	0.188	0.432
ENV+PM25	37	161.951	13.047	0.001	0.193	0.444
HINV	38	167.555	15.014	0.001	0.182	0.420
PM25	38	168.571	16.030	<0.001	0.179	0.416
GDP	38	168.687	16.146	<0.001	0.179	0.415
GDP+HINV	37	167.000	18.097	<0.001	0.181	0.421
BF	38	172.242	19.701	<0.001	0.171	0.399
FOOD	38	173.284	20.743	<0.001	0.169	0.395
ENV+HS	37	170.620	21.717	<0.001	0.172	0.405
HS	38	174.627	22.086	<0.001	0.166	0.389
ENV	38	175.594	23.053	<0.001	0.164	0.384

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Table S5. Structural equation models considered in the model set correlating socio-economic and environmental variables to the **diarrhoeal disease** index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
ALL	30	120.696	-	0.560	0.303	0.595
GDP+GOV	37	148.443	2.284	0.179	0.231	0.486
H2O	38	152.496	2.700	0.145	0.222	0.470
GOV	38	155.533	5.737	0.032	0.213	0.456
ENV+H2O	37	152.001	5.842	0.030	0.220	0.470
ENV+PM25	37	153.062	6.903	0.018	0.217	0.465
ENV+HS+H2O	36	149.459	6.938	0.017	0.225	0.479
HINV	38	158.586	8.789	0.007	0.205	0.441
PM25	38	159.810	10.014	0.004	0.201	0.436
GDP	38	160.097	10.300	0.003	0.201	0.434
FOOD+BF	37	157.156	10.997	0.002	0.206	0.446
GDP+HINV	37	158.047	11.887	0.001	0.203	0.442
ENV+HS	37	162.491	16.332	<0.001	0.192	0.421
HS	38	166.442	16.645	<0.001	0.185	0.405
FOOD	38	166.467	16.670	<0.001	0.184	0.405
BF	38	166.941	17.144	<0.001	0.183	0.403
ENV	38	168.055	18.259	<0.001	0.181	0.398

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Table S6. Structural equation models considered in the model set correlating socio-economic and environmental variables to the **infectious diseases** index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
GDP+GOV	37	130.453	-	0.347	0.292	0.512
GDP	38	134.388	0.297	0.300	0.281	0.494
H2O	38	136.034	1.943	0.132	0.275	0.485
HINV	38	136.909	2.818	0.085	0.272	0.481
GDP+HINV	37	134.273	3.820	0.051	0.278	0.492
ENV+H2O	37	135.853	5.400	0.023	0.272	0.484
GOV	38	139.827	5.736	0.020	0.262	0.465
PM25	38	140.448	6.358	0.014	0.260	0.462
ENV+PM25	37	137.516	7.063	0.010	0.266	0.475
ENV+HS+H2O	36	134.917	8.102	0.006	0.272	0.486
HS	38	143.296	9.205	0.003	0.250	0.447
ENV	38	144.060	9.970	0.002	0.248	0.443
FOOD	38	144.442	10.351	0.002	0.246	0.441
ENV+HS	37	141.322	10.869	0.002	0.253	0.455
BF	38	145.564	11.473	0.001	0.243	0.435
ALL	30	118.138	13.148	<0.001	0.314	0.556
FOOD+BF	37	143.802	13.349	<0.001	0.245	0.442

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Table S7. Structural equation models considered in the model set correlating socio-economic and environmental variables to the **injury** index among countries. **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables. Values in the table refer to: **df** = degrees of freedom; χ^2 = chi-square; **ΔBIC** = difference in Bayesian information criterion of the top-ranked model and the model in question; ***w*BIC** = BIC model weight[25]; **NCI** = McDonald's non-centrality index[22] (goodness-of-fit); **IFI** = Bollen's incremental fit index[23] (goodness-of-fit).

model	df	χ^2	ΔBIC	*w*BIC	NCI	IFI
H2O	38	141.714	-	0.754	0.255	0.517
ENV+H2O	37	141.315	3.238	0.149	0.253	0.517
ENV+HS+H2O	36	138.993	4.554	0.077	0.258	0.525
GDP+GOV	37	145.889	7.813	0.015	0.239	0.496
ALL	30	124.816	12.203	0.002	0.287	0.575
GDP	38	154.535	12.820	0.001	0.216	0.458
HINV	38	157.518	15.804	<0.001	0.208	0.444
GOV	38	157.827	16.113	<0.001	0.207	0.442
GDP+HINV	37	154.195	16.118	<0.001	0.214	0.457
FOOD	38	158.264	16.549	<0.001	0.205	0.440
ENV+PM25	37	155.291	17.214	<0.001	0.211	0.452
FOOD+BF	37	155.569	17.492	<0.001	0.210	0.451
PM25	38	161.768	20.054	<0.001	0.196	0.424
ENV+HS	37	161.088	23.011	<0.001	0.195	0.425
HS	38	165.465	23.750	<0.001	0.187	0.407
ENV	38	166.717	25.003	<0.001	0.184	0.401
BF	38	170.040	28.326	<0.001	0.176	0.386

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

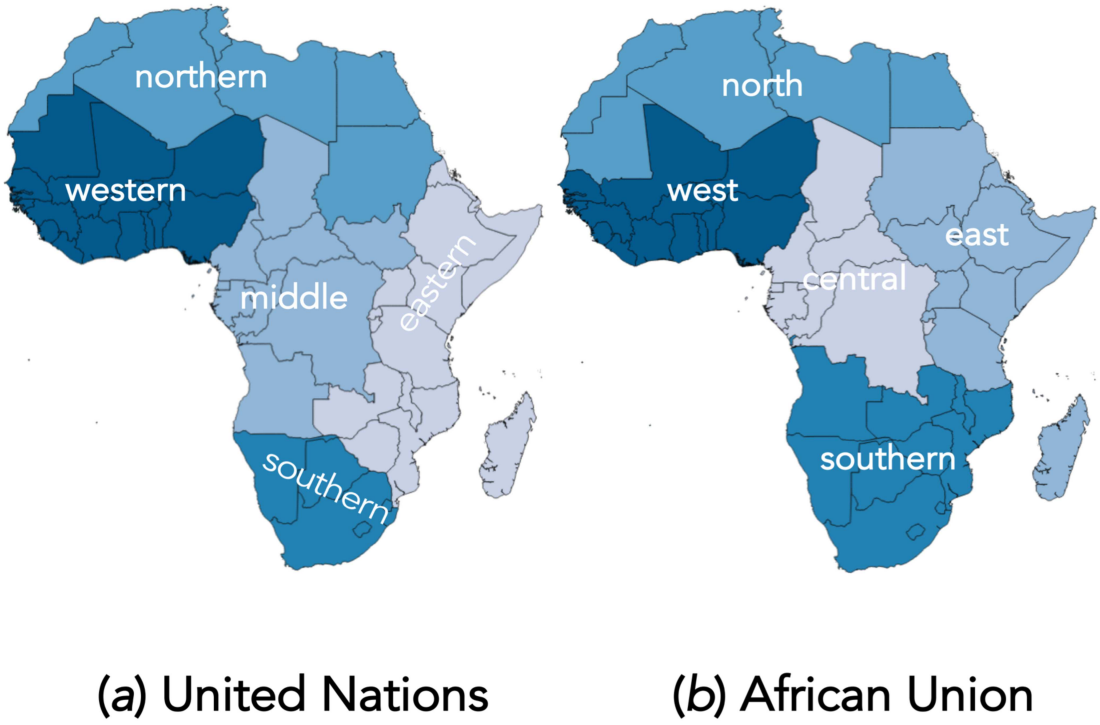
General linear mixed-effects models

We employed general linear mixed-effects models (GLMM) with a Gaussian error distribution and identity links using the `lmer` function from the *lme4* package[26] in R, with a 'region' random effect according to two different regionalizations for the African continent to account for any broad-scale spatial non-independence. Although including all data in this way ignores other non-independence issues (e.g., country adjacencies), it identifies which correlates are likely to provide some explanatory power.

The two regionalization schemes we used were (*a*) the five United Nations regions (northern, western, middle, eastern, southern; www.un.org), and (*b*) the five African Union regions (north, west, central, east, southern; www.au.int). (Fig. S1). We ranked 13 candidate models for each regionalization random-effect scenario using Akaike's information criterion[27] (AIC), expressing model probability as an AIC weight (*w*AIC)[25]. We also calculated the marginal R^2 of each resampled GLMM (R_m) as a measure of goodness of fit and the contribution of the fixed effects to explaining variance in the response variable (environmental performance rank)[28]. We fit all models to the original configuration of the data presented in the main text. Model rankings and associated metrics are given in Tables S8-S9).

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Figure S1: Two regionalisation schemes according to the (*a*) United Nations, and (*b*) African Union. Geographic data for country outlines from maplibrary.org (public domain). Regionalisation data for the five United Nations regions from www.un.org (public domain), and for the five African Union regions from www.au.int (public domain).



Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Table S8. General linear mixed-effects models considered in the model set correlating socio-economic and environmental variables to the composite child-health index among countries. All models include a random effect following the United Nations regions (northern, western, middle, eastern, southern; Fig. S1*a*). **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables; ***intercept-only*** = model including only the intercept (i.e., no fixed effects). Values in the table refer to: ***k*** = number of model parameters; **LL** = log-likelihood, **ΔAIC** = difference in Akaike's information criterion[27] of the top-ranked model and the model in question; ***w*AIC** = AIC model weight[25]; $\mathbf{R_m}$ = marginal R^2 as a measure of goodness-of-fit[28].

model	*k*	LL	ΔAIC	*w*AIC	R_m
ALL	12	-40.710	-	0.452	63.555
GDP+GOV	5	-39.371	0.536	0.346	51.612
H2O	4	-41.511	3.336	0.085	50.196
ENV+H2O	5	-42.478	4.990	0.037	49.558
ENV+HS+H2O	6	-43.000	4.999	0.037	53.107
GDP	4	-42.238	5.802	0.025	47.473
GDP+HINV	5	-42.344	7.274	0.012	47.915
GOV	4	-43.248	9.332	0.004	31.897
HINV	4	-44.674	11.301	0.002	39.121
FOOD	4	-48.318	18.783	<0.001	22.539
FOOD+BF	5	-48.797	19.872	<0.001	23.699
ENV+PM25	5	-49.261	20.461	<0.001	23.613
PM25	4	-49.833	22.497	<0.001	16.506
ENV+HS	5	-51.168	24.418	<0.001	10.505
ENV	4	-51.066	24.551	<0.001	6.249
HS	4	-51.299	25.046	<0.001	5.389
intercept-only	3	-51.351	25.211	<0.001	-
BF	4	-52.149	27.181	<0.001	0.068

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

Table S9. General linear mixed-effects models considered in the model set correlating socio-economic and environmental variables to the composite child-health index among countries. All models include a random effect following the African Union regions (north, west, central, east, southern; Fig. S1*b*). **HS** = mean household size; **GDP** = per capita gross domestic product (corrected for purchasing power parity); **ENV** = composite environmental performance index; **H2O** = proportion of the population with access to improved water and sanitation services; **PM25** = population-weighted average surface particulate matter < 2.5 µm; **HINV** = per capita health investment; **BF** = proportion of infants exclusively breastfed for the first six months of life; **FOOD** = per capita caloric availability; **GOV** = governance quality; ***ALL*** = model including all predictor variables; ***intercept-only*** = model including only the intercept (i.e., no fixed effects). Values in the table refer to: ***k*** = number of model parameters; **LL** = log-likelihood, **ΔAIC** = difference in Akaike's information criterion[27] of the top-ranked model and the model in question; ***w*AIC** = AIC model weight[25]; $\mathbf{R_m}$ = marginal R^2 as a measure of goodness-of-fit[28].

model	*k*	LL	ΔAIC	*w*AIC	R_m
ALL	12	-40.293	-	0.448	63.487
GDP+GOV	5	-39.707	0.771	0.305	50.063
H2O	4	-40.912	2.660	0.119	50.668
ENV+H2O	5	-41.951	4.420	0.049	50.171
ENV+HS+H2O	6	-42.574	4.887	0.039	51.740
GDP	4	-42.757	6.478	0.018	44.320
GDP+INV	5	-42.324	7.314	0.012	43.660
HINV	4	-42.856	7.758	0.009	39.598
GOV	4	-43.790	10.222	0.003	31.370
FOOD	4	-49.046	20.182	<0.001	21.696
ENV+PM25	5	-49.261	20.462	<0.001	22.215
FOOD+BF	5	-49.520	21.265	<0.001	22.896
PM25	4	-49.694	22.126	<0.001	16.729
ENV+HS	5	-51.029	24.150	<0.001	11.760
HS	4	-51.120	24.643	<0.001	7.595
ENV	4	-51.270	24.940	<0.001	7.145
intercept-only	3	-51.697	25.857	<0.001	-
BF	4	-52.478	27.810	<0.001	0.124

Bradshaw CJA, *et al. BMJ Open* 2020; 9:e029968. doi: 10.1136/bmjopen-2019-029968

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