

1 **Global human population ended self-facilitation in the 1950s**

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36
37 **Abstract**

38 Applied to human populations, the ecological concept of carrying capacity is necessarily
39 complicated because human beings are the “ultimate ecosystem engineers” who deliberately
40 and successfully moderate their environment for their benefit. For at least that last few
41 hundred years, human ingenuity, access to massive stocks of fossil fuels, and technological
42 development have driven facilitation whereby increasing human abundance promoted higher
43 population growth rates. However, this positive relationship broke down during the 1950s,
44 and by 1962, the global human population entered a negative phase where the growth rate
45 consistently declined as population increased. The onset of the negative phase was
46

47 approximately contemporaneous with a global biocapacity deficit that began in 1970 and has
48 increased ever since. The onset of the negative phase varies regionally, with the lowest-
49 income regions entering this phase later than higher-income regions. A Ricker logistic model
50 fitted to the negative phase predicts that the global population could reach 11.6 to 12.3 billion
51 people between 2065 and 2074. The same model fitted to the facilitation phase predicts a
52 maximum sustainable population of 2.5 billion people that Earth's carrying capacity might be
53 able to maintain over a longer time period. This is in line with economics-based estimates of
54 equitable wealth distribution (3.3 billion people) and an ecological footprint of 0.5 planets
55 (2.35 billion people). The negative phase also correlates strongly with the trend in global
56 temperature anomaly. The Earth cannot sustain the future human population, or even today's,
57 without a major overhaul of socio-cultural practices for using land, water, energy,
58 biodiversity, and other resources. Sustainable development therefore continues to face the
59 challenge of meeting the needs and aspirations of current societies while simultaneously
60 ensuring that future generations can meet their own.

61
62 *Key words:* climate change, global human carrying capacity, population growth
63

64 **Introduction**

65 Human beings undoubtedly have the best-studied demography of any species, yet for most of
66 human existence, there were no accurate censuses of population size, nor estimates of age
67 structure, birth, or death rates. However, since the 1950s when global population censuses
68 began in earnest¹, we now have an in-depth appreciation for how population structure has
69 changed in response to shifting economics², social dynamics³, education⁴, culture^{5,6}, health
70 interventions^{7,8}, family planning^{2,9}, marriage patterns¹⁰, migration^{2,11}, warfare¹², and
71 disease¹³, among others. Yet despite the wealth of data and analyses on human demography,
72 we still have a poor understanding of how the global human population responds to its own
73 processes of self-facilitation and limitation², especially considering we have data for only a
74 tiny fraction of the history of *Homo sapiens*.

75 *Carrying capacity* is an ecological concept describing the long-term average maximum
76 number of individuals of a particular species (typically measured as a density in individuals
77 per unit area and denoted K) an environment can sustain indefinitely given the available
78 regenerative resources¹⁴⁻¹⁶. In mathematical terms, K can be calculated as the long-term mean
79 population size (N) where the *per capita* rate of exponential population change (r) approaches
80 zero^{14,15} (Supplementary Information Appendix I, Fig. S1). This phenomenological
81 relationship is the *ensemble* expression of *component* feedback¹⁷ — the process by which
82 interactions among individuals and groups affect component demographic rates (e.g.,
83 survival, fertility, and dispersal). Variation in the components in turn 'feed back' directly or
84 indirectly to alter population size and the demographic rates themselves¹⁸. There are two
85 main types of phenomenological relationship between r and N — *negative* where the rate of
86 population growth declines as population size increases, and *facilitation*, a special case where
87 the rate of population growth rises as the population increases¹⁸.

88 Applied to human populations, the concept of carrying capacity is necessarily complicated
89 because human beings are the "ultimate ecosystem engineers" who deliberately and

90 successfully moderate their environment for their benefit^{19,20}. In contrast to non-human
91 species limited by the regenerative resource base on which they directly depend, modern
92 humans have essentially eradicated the limiting feedback from resource depletion via the
93 exploitation of fossil fuels. Other reasons why the concept of ecological carrying capacity
94 applied to human populations is cumbersome is because of the huge variation in the amount
95 of resources used and environmental damage caused by individuals²¹, the access to non-
96 renewable stocks of resources that can complement regenerative resources, and the difficulty
97 in determining what technological innovations and standards of living are considered
98 ‘acceptable’¹⁹ at any given population size and fertility rate. The latter reason is possibly the
99 most intractable element when applying carrying capacity to human beings, because K has
100 different interpretations depending on the economic system and technologies at play, whether
101 societies endeavour to reduce inequality, over what period of time one decides to apply the
102 criteria, and how much environmental damage we are willing to endure or accept^{20,22}, and at
103 which point the environmental damage is so great and the human load so high, that those
104 physical conditions start to limit the size of human populations directly. In addition, Rees²³
105 argued that technological innovation often does not increase K *per se*, but only the efficiency
106 of resource use, which can create the illusion of increase while shielding people from
107 perceiving the permanent damage to the resource base.

108 Another complication is that despite the well-documented, planetary-wide ecological and
109 extinction crisis underway^{19,24,25} made possible by the exploitation of fossil fuels, and the
110 observation that human societies have long ago exceeded the Earth’s ‘biocapacity’ (i.e., the
111 productivity of ecological assets, including cropland, grazing land, forest land, fishing
112 grounds, and built-up land)²⁶, gross measures of human wellbeing are generally at historical
113 highs; for example, absolute poverty is declining²⁷ (although country-specific poverty is
114 rising²⁷), as is child mortality²⁸, while longevity is mostly increasing²⁹; however, potentially
115 exacerbated by the effects of COVID-19, under-nutrition has increased³⁰ by ~ 30% between
116 2017 and 2021, and obesity is rising²⁹. This apparent paradox has come at a cost to the
117 stability of humanity’s life-support system, and a massive increase in dependence on fossil
118 fuels, which is in turn threatening the very life-support system that sustains this population
119 via resultant climate change, while also blinding societies to finite, regenerative biological
120 resources as long as fossil fuel-based alternatives are available. The pressures on the
121 biosphere also stem from persistent overuse, including past carbon emissions. This means
122 that the stressors are the outcome of cumulative, historical overuse, not just current activities.
123 Together, these stressors limit continued improvement, and are instead likely to or have
124 already started to reduce standards of living^{24,31}.

125 As a result, there have been many scientific discussions of human carrying capacity^{16,19-}
126 ^{22,32-34}, with no clear consensus on either its value²⁰ or even relevance to modern human
127 society. However, most appear to agree that for human beings, ‘optimum’ carrying capacity
128 is considerably lower than ‘maximum’ (or ‘biophysical’) carrying capacity^{21,22,33}. The
129 qualifier ‘optimum’ appears to refer to a feedback connected to an enhancement of wellbeing
130 via socio-economic development and environmental integrity¹⁹, such as the maximum
131 number people that can be sustained at a minimum standard of living^{33,34}, rather than a
132 maximum density dictated instead by famine, disease, and war³².

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134 We show here, using well-established demographic analyses from ecology, that the
135 available data describing trends in human population size over the last century identify both
136 realistic optimum (~ 2.5 billion) and maximum (11.55–12.26 billion) global population, and
137 that human societies shifted from a long period of facilitation (more people = higher
138 instantaneous exponential rate of annual increase) at the end of the 1940s, to one where
139 further increases in population size were associated with consistently declining growth rate
140 beginning in the 1960s.

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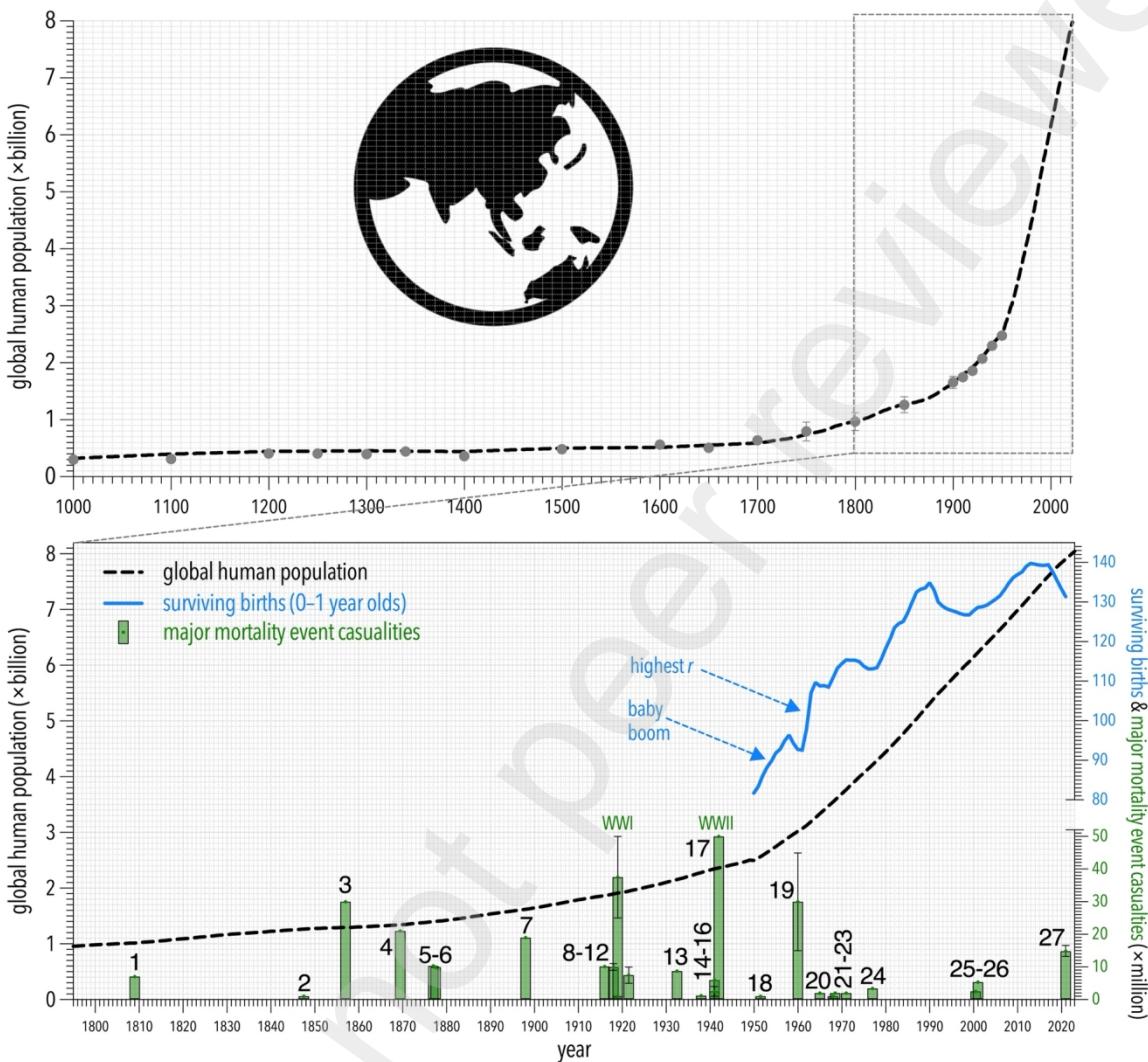
142 Methods and results

143 We first examined the available estimates of human population size back to 1000 AD, given
144 that the period since then includes estimates corroborated by several analyses^{1,35–43}. From
145 these data, we calculated the instantaneous (annual) exponential rate of change ($r =$
146 $\log_e(N_{t+1}/N_t)$) and population size (N) at year t from 1800 to 2023 (because global population
147 sizes are available in annual increments during this period⁴¹).

148 The trajectory of the global human population slowly increased (mean $r = 0.0009$) from an
149 estimated 323 million in 1000 AD to 592 million in 1700 (Fig. 1a). From the onset of the
150 Industrial Revolution in the mid-18th Century, the rate of increase expanded considerably
151 (mean $r = 0.005$, or 5 times the rate observed between 1000 and 1700 AD) to produce a
152 global population of 985 million by 1800 (Fig. 1a). Population increase was consistently
153 positive thereafter, despite at least 27 major mortality events (each with ≥ 1 million estimated
154 casualties counted as excess deaths), four of which had ≥ 30 million casualties each (i.e.,
155 Taipeng rebellion⁴⁴, ‘Spanish’ influenza pandemic⁴⁵, World War II⁴⁶, and the Chinese
156 famine⁴⁷; Fig. 1b). Following World War II when global population censuses began in
157 earnest¹, the global human population expanded at its fastest rate ever², reaching an average
158 rate of increase of $r = 0.02$ between 1950 and 1970. This increase is known as the post-World
159 War II Baby Boom of the 1950s and 1960s (Fig. 1b).

160

161 **Figure 1.** Global human population size from 1000 to present (main figure) and from 1800 to present^{1,37,39,41}
 162 (black line; inset). Dark grey circles with confidence limits derived from the upper and lower estimates of
 163 several sources^{35,36,38,40,42,43}. Inset shows approximate magnitude (green bars; casualties) of major human
 164 mortality events (with ≥ 1 million deaths) since 1800 (right y axis; green; see references below figure for
 165 sources).



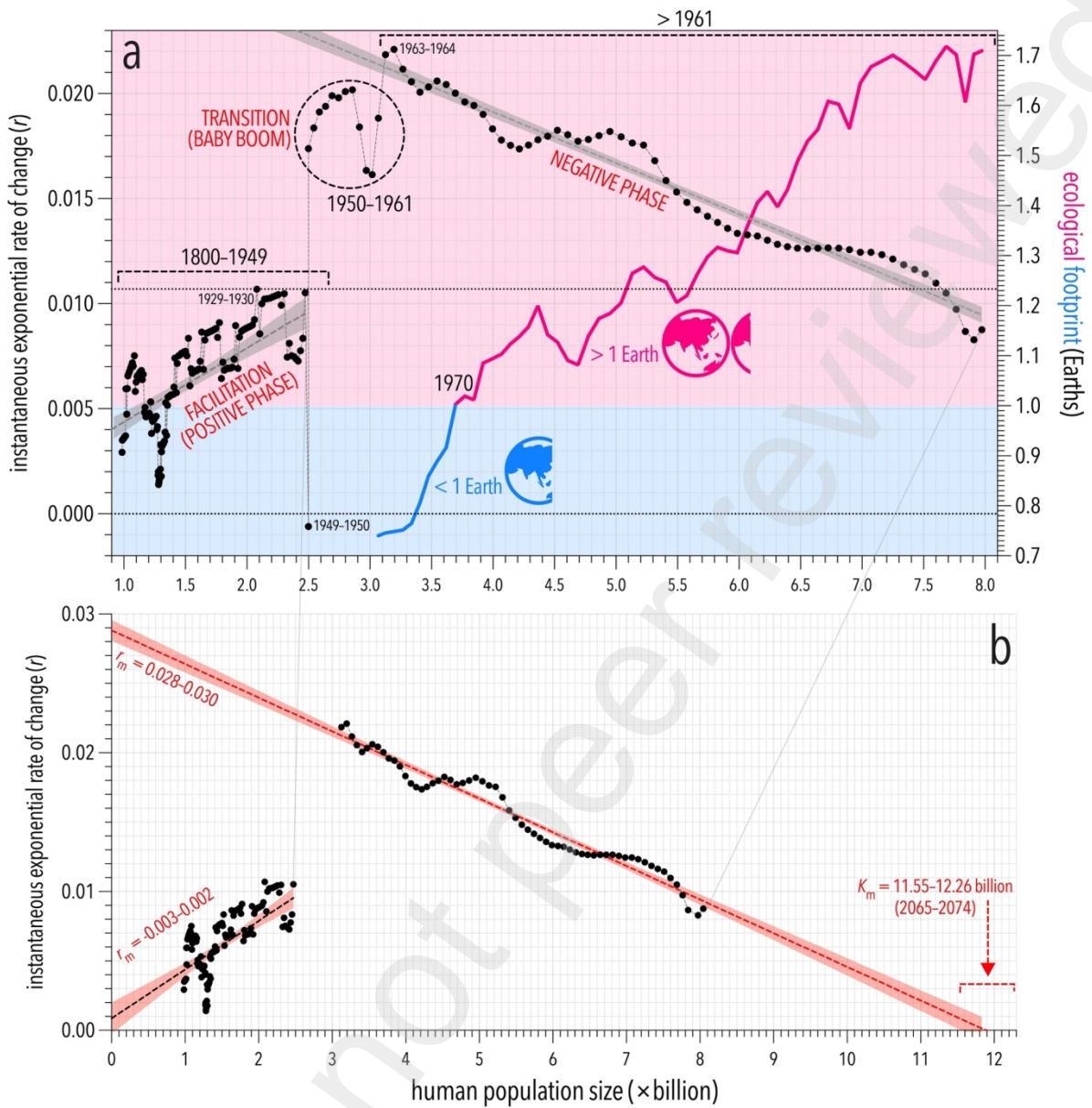
166 mortality events listed: 1. Napoleonic wars (7 million)⁴⁸, 2. Irish famine (1 million)⁴⁹, 3. Taiping rebellion (30 million)⁴⁴, 4. Dungan revolt
 167 (21 million)⁵⁰, 5. British India famine (10.3 million)⁵¹, 6. northern Chinese famine (10 million)⁵², 7. Indian famine (19 million)⁵², 8. World
 168 War I (10.1 million)⁴⁶, 9. Iranian famine (9–11 million)⁵³, 10. influenza pandemic (25–50 million)⁴⁵, 11. Russian civil war (1 million)⁴⁶, 12.
 169 Russian famine (5–10 million)⁵⁴, 13. Soviet famine (8.7 million)⁵⁵, 14. Chinese civil war (1.2 million)⁴⁶, 15. 2nd Sino-Japanese war (1–4
 170 million)^{46,56} and 16. famine (6 million)⁵⁶, 17. World War II (50 million)⁴⁶, 18. Korean war (1 million)⁴⁶, 19. Chinese famine (15–45
 171 million)⁴⁷, 20. Vietnam war (2 million)⁴⁶, 21. Nigerian civil war (1 million)⁵⁷ and 22. famine (2 million)⁵⁸, 23. Chinese Cultural Revolution
 172 (2 million)⁴⁶, 24. Cambodian genocide (3.4 million)⁵⁹, 25. 2nd Congo civil war (2.5 million)⁶⁰ and 26. famine (5.4 million)⁶¹, 27. COVID-19
 173 (13.23–16.58 million)⁶²

174
 175 Examining the linear relationship between the annual exponential rate of change (r) and
 176 global population size (N) based on the phenomenological ‘Ricker’ logistic model¹⁷ (Fig. 2)
 177 shows a striking shift during the 1950s from facilitation (positive) to a negative phase. From
 178 1800 to 1949, there was a clear signal of facilitation — population growth rate increased with
 179 increasing global population size¹⁸. This means that per-capita fitness (survival, reproduction)
 180 benefitted as the population increased, indicative of self-reinforcement via technological and
 181 socio-economic improvements to living conditions¹⁹.

183 The post-WWII Baby Boom during the 1950s precipitated a large increase in the growth
184 rate, but de-stabilised the relationship between r and N_t (the negative r shown for 1949–1950
185 is an artefact of global census data being standardised from 1950 onward — the human
186 population did not decrease during this period and then recover in one year). However, by
187 1961, the global human population became locked into a negative phase (the highest-
188 recorded r was from 1962–1963; Fig. 2a), whereby further increases in the population were
189 accompanied by decreasing population growth rate (i.e., Fig. 2a).

190

191 **Figure 2.** (a) Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and
192 population size (N) at year t from 1800 to 2023. There is a positive relationship between r and N_t 1800 and 1949,
193 indicating facilitation. The dotted horizontal line intersecting 1929–1930 indicates the highest r observed during
194 the facilitation phase (0.011). The negative r shown for 1949–1950 is an artefact of global census data being
195 standardised from 1950 onward. However, following WWII through the 1950s there was a period of transition
196 toward high r , but no relationship with N_t , and then the establishment of a negative $r \sim N_t$ relationship from
197 around 1961–1962 to the present. Also shown on the right y axis is the ecological footprint expressed in terms of
198 number of Earth's required to meet global human consumption — at 1 ‘Earth’, the global ecological footprint
199 (ecological assets the global population requires to produce the natural resources it consumes and to absorb its
200 wastes) equals the Earth's biocapacity (productivity of ecological assets, including cropland, grazing land, forest
201 land, fishing grounds, and built-up land)²⁶. The global ecological footprint has exceeded the Earth's biocapacity
202 since 1970 (transition from blue to pink). (b) Extending the fitted relationship between r and N_t to where $r(y) =$
203 0 indicates maximum (biophysical) global population size ($K_m = -\text{intercept} \div \text{slope}$). Assuming no deviation
204 from this expected relationship, $K_m = 11.55$ to 12.26 billion people predicted to occur between 2065 and 2074.
205 Extending the negative relationship back to $N_t(x) = 0$ (intercept) indicates the theoretical maximum rate of
206 increases predicted for human beings in the absence of mortality (r_m): 0.0281 to 0.0296, which agrees well with
207 the cohort-based prediction⁶³ of r_m for humans = 0.03. Extending the facilitation relationship back to $N_t(x) =$
208 0 (intercept) gives $r_m = -0.003$ to 0.002 (median = 0.001), the upper limit of which is close to the predicted rate
209 of hunter-gatherer population growth derived from cohort-based models ($r_m = 0.003$)⁶³. Red shading around
210 Ricker logistic fits indicates 95% confidence intervals.



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213 The negative phase beginning in 1962 approximately coincided with the onset of global
 214 consumption (ecological footprint) exceeding the Earth's biocapacity, measured as the
 215 number of Earths required to meet consumption rates²⁶. By 1970, the Earth transitioned to a
 216 global biocapacity deficit (required Earths > 1; Fig. 2a) and has remained so since, likely
 217 driven by the rapid fossil fuel-enabled expansion of economic activities, which became a
 218 global phenomenon following World War II.

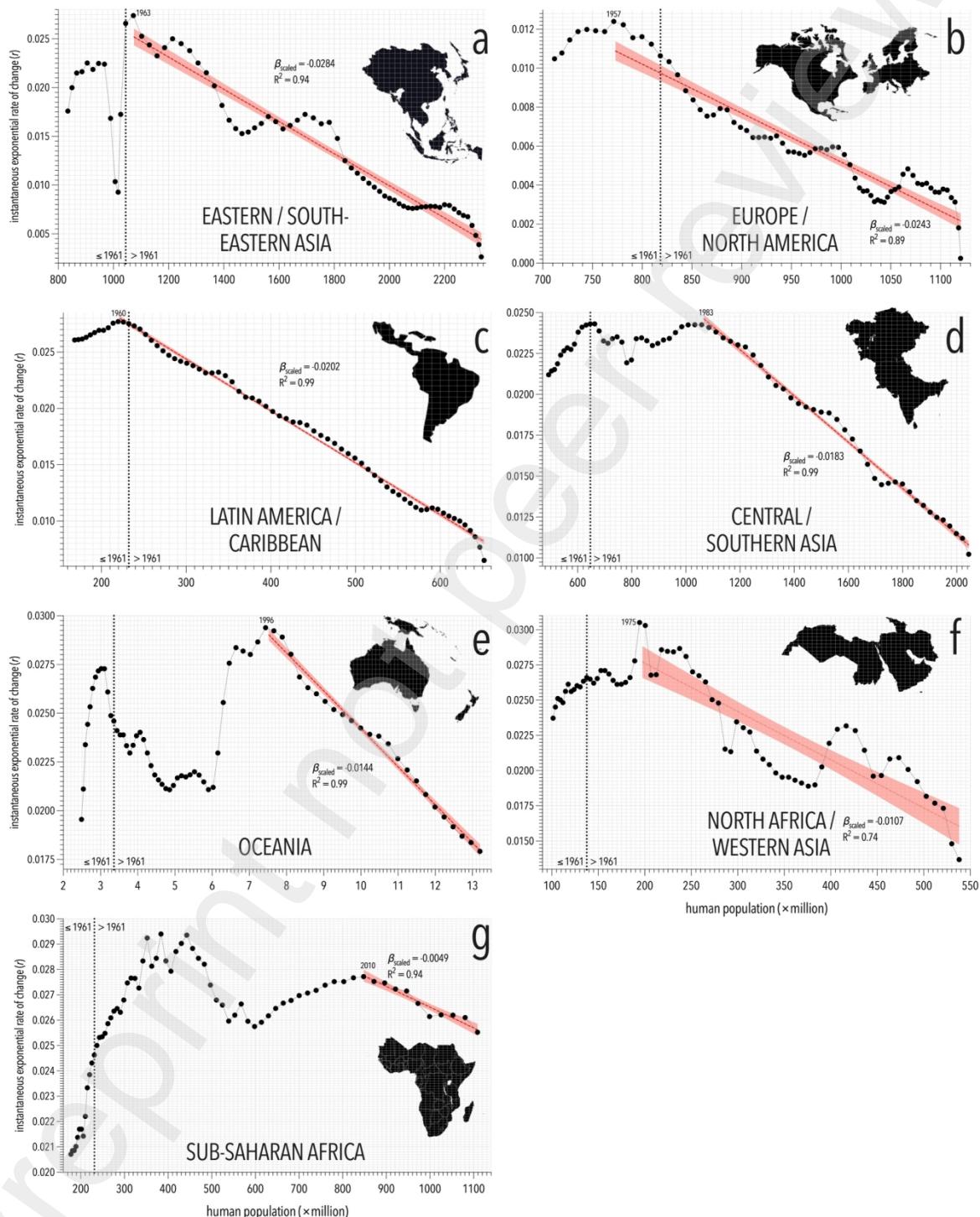
219 A phenomenological Ricker logistic model¹⁷ predicts that when a population's $r = 0$
 220 (stability, or zero population 'growth'), the quotient of the negative slope and intercept of the
 221 linear fit of $r \sim N_t$ estimates an expected maximum population size. This is distinct from a
 222 ('biophysical')³³ carrying capacity of the environment²¹, which would be a population size
 223 that could be sustained, and would not just operate on stock depletion as it does currently.
 224 This maximum population is reached at the point when total births are perfectly offset by
 225 total deaths. From the global data shown in Fig. 2, this is predicted to occur at 11.55 to 12.26

226 billion people, and assuming no deviation from the expected relationship, would occur
227 between 2065 and 2074 (Fig. 2b). As additional reality checks of the relationships, extending
228 the Ricker logistic model to the intercept (where $N_t = 0$) gives the theoretical maximum rate
229 of increase⁶⁴ ($r_m = 0.028\text{--}0.030$), which agrees well with theoretical predictions of maximum
230 population growth for humans ($r = 0.03$) in the absence of mortality⁶³. Likewise, extending
231 the depensation relationship back to $N_t = 0$ gives⁶⁵ $r_m = -0.003\text{--}0.002$ (median = 0.001),
232 which also agrees with the realised r_m derived from cohort-based models for hunter-
233 gatherers⁶³.

234 Sustainable carrying capacity (K_s) is considerably lower than ‘maximum’ population size
235 predicted at $r = 0$ (K_m)^{21,22,33}. This is because K_m is enabled by stock depletion, which allows
236 people temporarily to overcome the limitations imposed by the regeneration rates of
237 biological resource supplies. The sustainable carrying capacity also depends on the average
238 standard of living per individual. The higher the consumption per person, the lower the
239 sustainable population K_s . A world at K_s is better than at K_m , because the former population
240 size is more likely to provide stabler economies, have less environmental impact, endure
241 longer, have fewer risks, and maintain more cultures and values^{22,66}. Given the evidence for
242 an abrupt switch from facilitation to a negative $r \sim N$ phase, we can conceivably estimate K_s
243 as the population size where facilitation produced maximum r . Taking the maximum r during
244 the 1800–1949 facilitation period ($r = 0.011$ from 1929–1930; Fig. 2a), this equates to a
245 global population of approximately 2.5 billion (Fig. 2a), which is remarkably close to the
246 global $K_s = 3.3$ billion estimated to allow all people to live in comfort economically³⁴. From
247 the perspective of a sustainable ecological footprint, assuming a consumption rate of 0.5
248 Earths to avoid over-consumption (compared to the 1.7 Earths consumed today) suggests the
249 current human population of 8 billion is approximately 3.4 times too large ($1.7 \div 0.5$), and
250 that a total global population of 2.35 billion ($8 \text{ billion} \div 3.4$) would be ‘sustainable’ at today’s
251 average material standard of living and current consumption distribution. Incidentally, global
252 population growth fell below $r = 0.011$ in 2018, and continues to decline since (Fig. 2a).

253 Treating the global population as a single unit potentially masks regional trends in the
254 onset and strength of the negative relationship between r and N . We therefore divided the
255 globe into seven regions defined by the United Nations (Sub-Saharan Africa, northern Africa
256 and western Asia, Europe and North America, Latin America and Caribbean, central and
257 southern Asia, eastern and south-eastern Asia, and Oceania). In each of the seven regions,
258 there is still a clear onset of the negative phase (Fig. 3), but in different years and with
259 different strengths (the latter defined as the slope of the relationship between r and N_t)¹⁷.
260

261 **Figure 3.** Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and
 262 population size (N) at year t from 1950 to 2023 for seven major global regions, sorted by descending magnitude
 263 of slope (rate of decline of r with increasing N ; see also Appendix II Fig. S2). N for each region are first scaled
 264 so that slopes are comparable (Appendix II Fig. S2). (a) eastern and south-eastern Asia, (b) Europe and North
 265 America, (c) Latin America and Caribbean, (d) central and southern Asia, (e) Oceania, (f) northern Africa and
 266 western Asia, (g) Sub-Saharan Africa. Vertical dotted line in each panel indicates the onset of the period of the
 267 negative phase (> 1961) from the global data (Fig. 2). The year when the negative phase began in each region
 268 shown in each panel. Red shading indicates 95% confidence interval of the Ricker logistic fit.

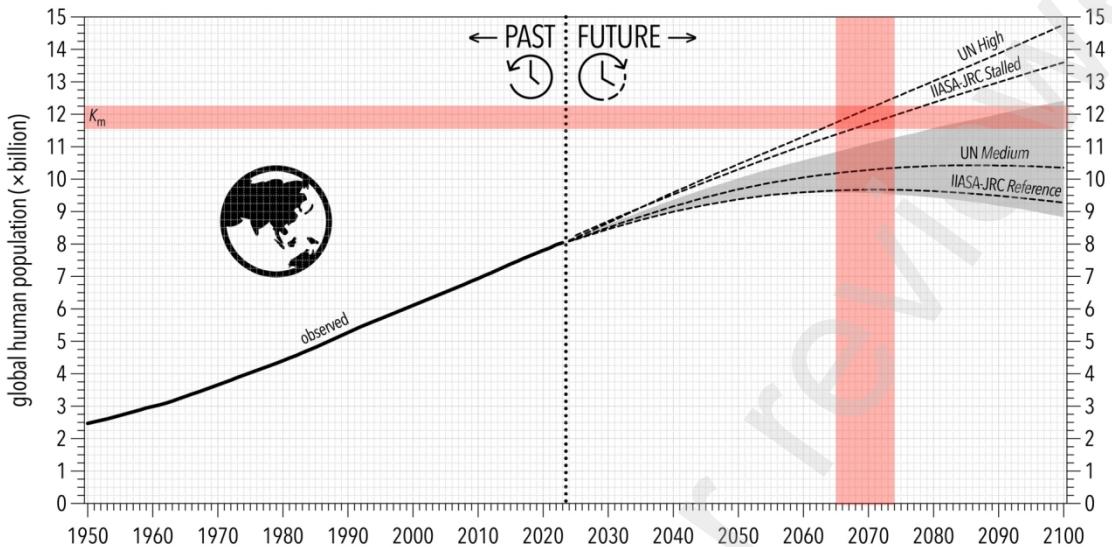


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The strongest rate of decline of r with increasing N during the negative phase occurred in eastern and south-eastern Asia (Fig. 3a), followed by Europe/North America, and Latin America/Caribbean (Fig. 3b-c; Supplementary Information Appendix II Fig. S2). These three regions also began their negative phase in the late 1950s or early 1960s (Fig. 3a-c) following the global trend (Fig. 2a). However, the remaining regions' negative phase began considerably later (after 1975; Fig. 3), with Sub-Saharan Africa being the last region to begin a negative phase in 2010 (Fig. 3g). Sub-Saharan Africa is also the region with the weakest rate of decline of r with N and greatest uncertainty in the estimate of K_m given the shortest-available time series during the negative phase (Fig. 3g; Supplementary Information Appendix II Fig. S2). However, even the African countries with the highest fertilities globally still show signs of a shift to a negative phase over the last few decades (Supplementary Information Appendix II Fig. S3). Extending the fits to $r = 0$ for each region's negative phase provides an estimate of K_m for each (Supplementary Information Appendix II Fig. S4) — the sum of which (12.0–13.7 billion) is only 8% (median) higher than that estimated with the global data combined (11.55–12.26 billion; Fig. 2b). While at least one period of facilitation is observed in all regions as well (Fig. 3), the regional data only go back to 1950 and cannot be used reliably to infer the form of the Ricker logistic model for the facilitation phase. Removing China from eastern and south-eastern Asia had little effect on the dynamics of the region, although China alone had the strongest rate of decline of r with increasing N compared to any region (Supplementary Information Appendix II Fig. S5).

Plotting the global prediction of K_m from the Ricker logistic model applied to the negative phase (Fig. 2b) against the most-plausible²⁸ projections of human population size to the end of this century (United Nations Population Division *Medium*, *High*, and *Probabilistic* scenarios¹, and the International Institute for Applied Systems Analysis and the European Commission's Joint Research Centre [IIASA-JRC] *Stalled* and *Reference* scenarios^{67,68}) demonstrates the best correspondence to the United Nations *High* and IIASA-JRC *Stalled* scenarios, but with plateauing occurring as in the United Nations *Medium* and *Probabilistic*, and the IIASA-JRC *Reference* scenarios (Fig. 4). This correspondence supports the higher predictions of population growth under the United Nations *High* and IIASA-JRC *Stalled* scenarios, but with stabilisation and possibly decline occurring from around 2070 (Fig. 4).

302 **Figure 4.** Past trajectory and future projections of the global human population from the most-plausible²⁸
 303 models of the United Nations (UN) and IIASA-JRC. Dotted black lines are the *Medium* and *High* scenarios
 304 from the UN¹, and the *Reference* and *Stalled* scenarios from the IIASA-JRC^{67,68}; grey-shaded area is the 95%
 305 confidence interval for the UN *Probabilistic Population Projections*¹. Red shading indicates the maximum
 306 human carrying capacity ($K_m = 11.55\text{--}12.26$) and timing (2065–2074) derived from Fig. 2b.

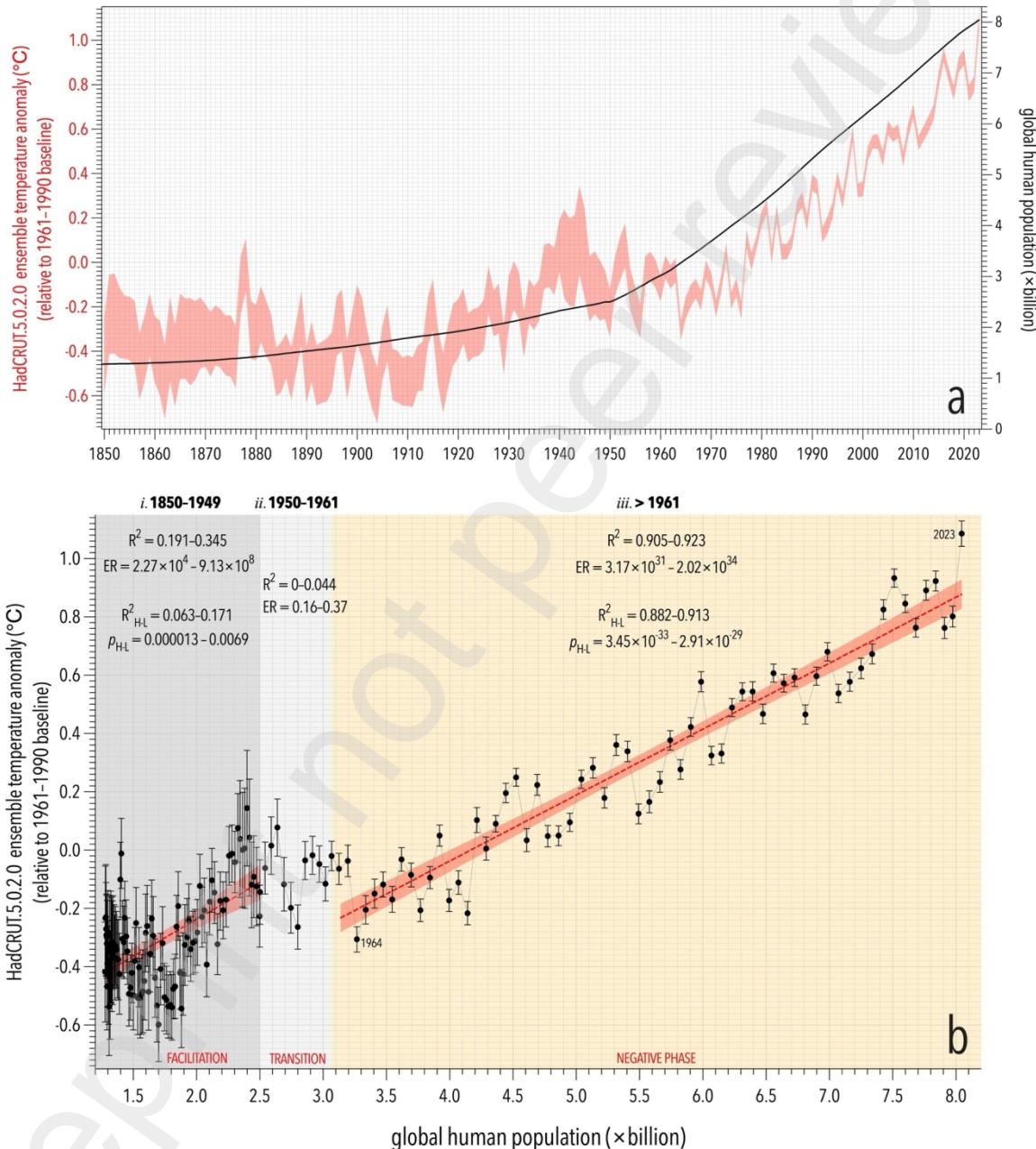


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 309 In addition to the global human footprint data indicating that consumption began to exceed
 310 the Earth's biocapacity in 1970 (Fig. 2a), we compared global human population size in the
 311 three main phases of facilitation, transition, and the negative (Fig. 2a) to the global
 312 temperature anomaly (Fig. 5a). We hypothesise that the strongest positive relationship
 313 between human population size and climate change occurs during the negative phase because
 314 of consumption externalities such as increasing natural resource exploitation and loss of
 315 biodiversity. This can result from societies in the period of declining r and resources
 316 subsequently driving environmental degradation. In contrast, societies in facilitation phases
 317 might have adequate resources to fuel increasing population growth rates. We uniformly
 318 sampled within the 95% confidence interval of the temperature anomaly (HadCRUT.5.0.2.0
 319 ensemble prediction⁶⁹ from the 1960–1991 baseline; data available from 1850 to the present)
 320 10,000 times and fit a linear model in R (function: *lm*) for each iteration. From these 10,000
 321 iterations we calculated the 95% confidence interval of the goodness of fit (R^2) and the
 322 evidence ratio (ER = Akaike's information criterion weight [$wAIC$] of the slope model \div
 323 $wAIC$ of the intercept-only model⁷⁰). Given temporal autocorrelation in the data structure, we
 324 also calculated the Hildreth-Lu (H-L) model accounting for first-order autocorrelation using
 325 the *orcutt* library⁷¹ in R, calculating the resampled 95% confidence interval of the
 326 Hildreth-Lu goodness of fit (R^2_{H-L}) and estimated Type I error (p_{H-L}).

327 As hypothesised, the global temperature anomaly was most strongly and positively
 328 correlated with the global human population size from 1962 onwards (Fig. 5b), even after
 329 accounting for temporal autocorrelation. Taking population size and per-capita consumption
 330 as predictors of temperature anomaly during the negative phase, population size emerges as
 331 the strongest predictor (Supplementary Information Appendix III). While there is also a
 332 positive correlation between temperature anomaly and human population size during the
 333 facilitation phase, it is weak ($R^2 = 0.191\text{--}0.345$; $R^2_{H-L} = 0.063\text{--}0.171$; Fig. 5b).

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Figure 5. (a) Global human population size (black line; right y axis) with the 95% confidence interval of the global temperature anomaly ($^{\circ}\text{C}$) derived from the HadCRUT.5.0.2.0 ensemble model⁶⁹ compared to the 1961–1990 baseline superimposed (red; left y axis). (b) Relationship between global human population size and temperature anomaly for the three main phases of human demography from 1850 to the present: *i.* facilitation (1850–1949; dark grey background shading), *ii.* transition (1950–1961; light grey background shading), and *iii.* the negative phase (1962–2023; peach background shading). Shown for each phase are the 95% confidence intervals of goodness of fit (R^2) and the evidence ratio (ER) for the linear models, and the Hildreth-Lu first-order autocorrelation model goodness of fit ($R^2_{\text{H-L}}$) and probability of Type I error ($p_{\text{H-L}}$). Red shading indicates 95% confidence interval of the linear fits in phases *i* and *iii*.



344

345 Discussion

346 Our predictions of global sustainable carrying capacity and maximum population size are the
347 first to be based on human population time series alone, and the simplicity of
348 phenomenological models¹⁷. A 2004 meta-analysis by van den Bergh and Rietveld²⁰

349 examined 51 studies that produced 94 estimates of a limit to the global human population.
350 Their median meta-prediction from these 51 studies was 7.7 billion people, but ranged from
351 650 million assuming a low-technology future where water availability is the main limiting
352 factor, to 288 billion under the assumption of the ‘best’ future technology for all countries
353 (with most estimates well above future projections). The uncertainty stems mainly from the
354 many different assumptions and dimensions considered in the projections. Others have
355 investigated the multivariate relationships of several human demographic rates and socio-
356 economic factors relative to human density across different spatial scales^{2,72-74}. For example,
357 Lutz and Qiang² found strong relationships between country-level total fertility rate and
358 population density (measured per area of arable land), but only a weak relationship between r
359 and population density. However, no previous study has investigated the evidence for
360 relationships between r and N at the global or regional scales as we did here.

361 The mechanisms driving the phenomenon of a decline in r within increasing global human
362 population size are necessarily complex, and likely include both direct and indirect pathways
363 leading to reduced population growth. Population growth is an ensemble property emerging
364 primarily from two main component demographic rates — fertility and survival¹⁷. In modern
365 human societies, fertility has the greatest effect on population growth², and indeed declined
366 during the negative phase globally and regionally (Supplementary Information Appendix II
367 Fig. S6). In contrast, survival (measured as the life expectancy at birth) increased throughout
368 the negative $r \sim N$ phase, despite population growth declining (Supplementary Information
369 Appendix II Fig. S7). However, while the onsets of the fertility declines were
370 contemporaneous with the beginning of the negative $r \sim N$ phase globally (Fig. S6a) and in
371 eastern/south-eastern Asia, Europe/North America, and Latin America/Caribbean (Fig. S6b-
372 d), they began earlier than the onset of the negative phase in central/southern Asia, Oceania,
373 north Africa/western Asia, and Sub-Saharan Africa (Fig. S6e-h). This suggests that any
374 population-related feedbacks were not the only drivers of declines in population growth rate.
375

376 The extent to which human population growth varies in response to (i) environmental
377 constraints such as access to sufficient land, and the efficiency with which we can extract and
378 consume fresh water, food, energy, and other material resources²⁰, (ii) decreasing fertility
379 from chemical exposure⁷⁵, and (iii) people choosing to reduce fertility (e.g., following the
380 principles outlined in the ‘demographic transition’ paradigm⁷⁶) are context-specific. Indeed,
381 any negative feedback is not required to act through direct biological mechanisms alone,
382 because even perceptions of population impacts⁶⁶ (e.g., crowding, competition for resources,
383 conflict) can be psychological determinants of human choices regarding fertility^{2,22,77},
384 empowerment, and reduced child mortality⁷⁸, ironically enhanced by the exploitation of fossil
385 fuels (e.g., household automation technologies), and have also played a strong role in fertility
reductions globally.

386 Regardless, the abrupt switch from a positive to a negative phase in the relationship
387 between r and N demonstrates that human ingenuity, technology, and social structure have
388 not enhanced human population growth since the 1950s. While estimates of human carrying
389 capacity derived from logistic models are straightforward and elegant, they cannot
390 necessarily predict the future. Our estimates assume that the form of the Ricker logistic
391 model will remain constant until $r = 0$, but global phenomena such as unmitigated climate
392 change and environmental collapse^{77,79,80} could, because of cumulative effects, decouple the

393 linear relationship between r and N sooner. Our approach also assumes that population size is
394 equivalent to *density* (individuals per unit area), the latter of which has more direct
395 mechanistic influences on human demography such as child morbidity and mortality⁸¹ and
396 total fertility rate² than population size *per se*. Nonetheless, the ensemble signal strength of
397 the negative phase is rather insensitive to variation in carrying capacity itself, although it
398 tends to underestimate component effects (i.e., how sensitive demographic rates are to
399 changes in population size) when abundance is trending strongly over time¹⁷. Given that the
400 global human population has been increasing consistently for thousands of years, and is still
401 at one of its highest rates of increase, the rate of the decline in r with increasing N we
402 observed in the global data is likely under- rather than over-estimated. This suggests that the
403 negative phase will continue unabated for several more decades at least.

404 Nonetheless, it is clear that Earth cannot sustain the future human population, or even
405 today's, without a major overhaul of socio-cultural practices for using land, water, energy,
406 biodiversity, and other resources¹⁹. As such, some form of societal downscaling (*sensu*¹⁹)
407 appears inevitable, whether achieved actively or in response to continued declines in
408 population growth²⁴. Instead of focusing on maximum carrying capacity, the number of
409 humans that can be safely imposed on the environment is a function of both population size
410 and per-capita consumption^{23,82}, both of which are continuing to rise⁶⁶. As such, any form of
411 future development under the umbrella of 'sustainability' must meet the needs and aspirations
412 of present societies while simultaneously ensuring that future generations can meet their
413 own³³. This cannot be achieved in the pursuit of a maximum population size, no matter how
414 well-defined, especially considering that smaller populations beget more individual and
415 environmental benefits⁶⁶. The tragedy is that human endeavour has short-circuited the
416 ultimately inevitable corrective feedback loops carrying capacity imposes, without replacing
417 them with humane and environmentally friendly corrective feedbacks.
418

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421

422 Author contributions

423 CJAB did the analyses. All authors contributed to writing the manuscript.
424

425 Author statement

426 The authors declare that they did the research without any commercial or financial
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428

429 Data and code availability

430 All data and R code necessary to repeat the analyses available at
431 github.com/cjabradshaw/globalHumanPopSwitch.
432

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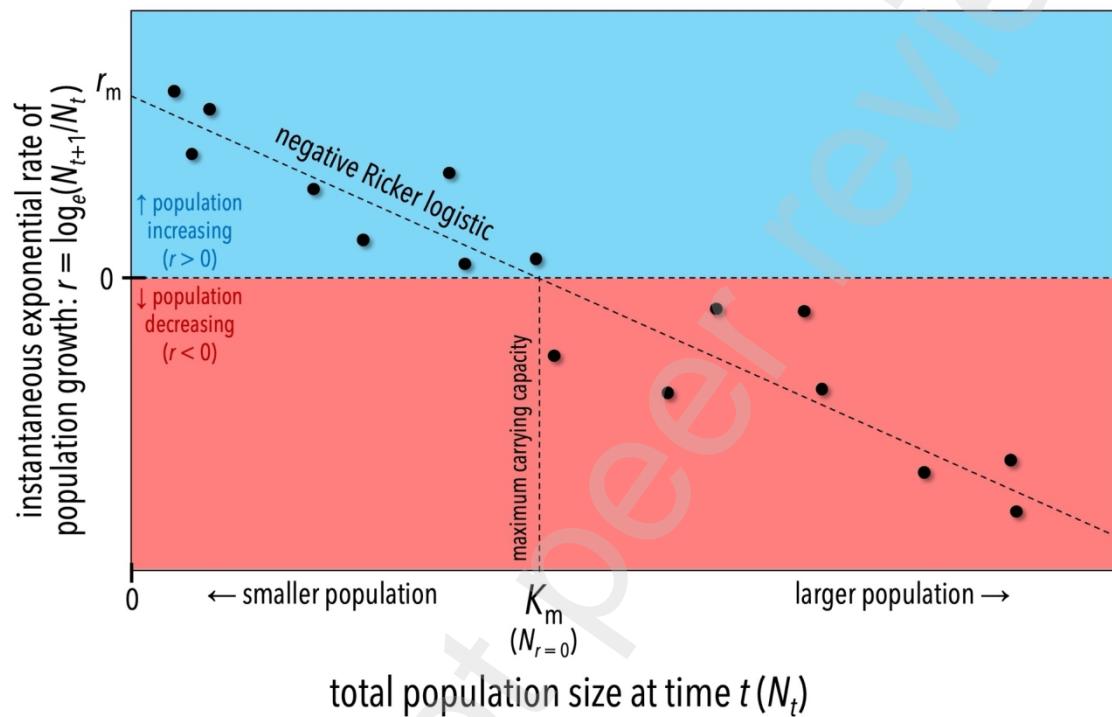
773 **Supplementary Information**

774

775 **Appendix I. Ricker logistic model**

776

777 **Figure S1.** Schematic of a phenomenological linear (Ricker logistic) model fit to the relationship between the
778 instantaneous exponential rate of population growth, $r = \log_e(N_{t+1}/N_t)$, where N = estimated population size
779 at census time t , and N_t . The relationship is negative, indicating a declining rate of population growth r with
780 increasing population size. The N where $r = 0$ indicates the maximum population size (K_m), and the r where $N =$
781 0 indicates the maximum (theoretical) rate of increase (r_m). The blue zone indicates when the population is
782 increasing between t and $t+1$, and the red zone indicates when the population is decreasing between t and $t+1$.

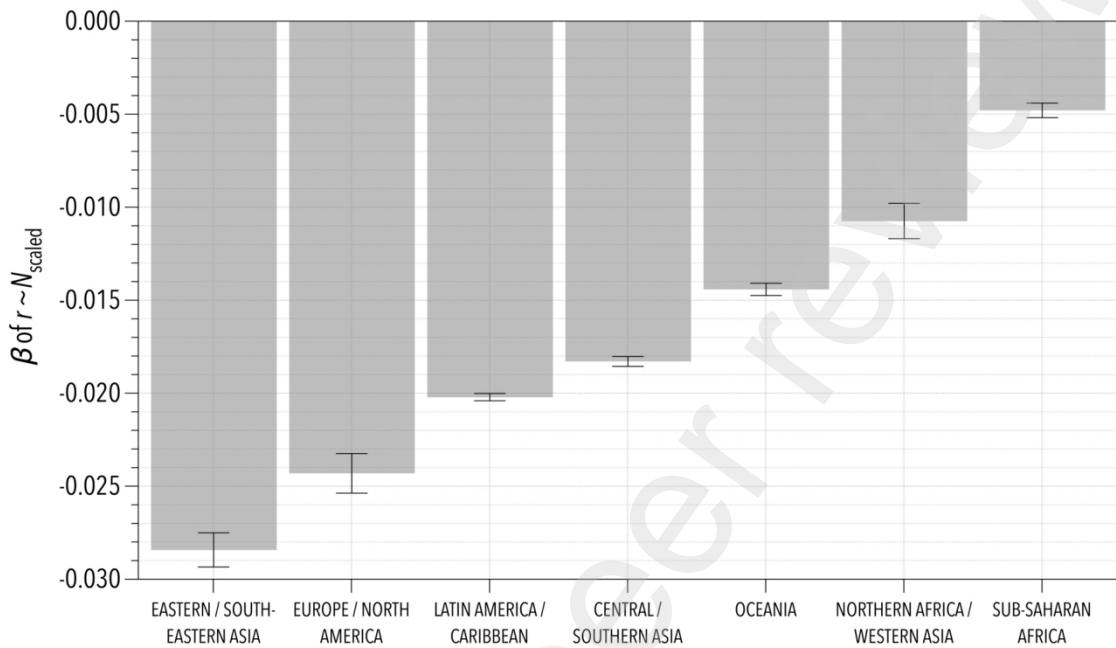


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784 **Appendix II. Supporting figures**

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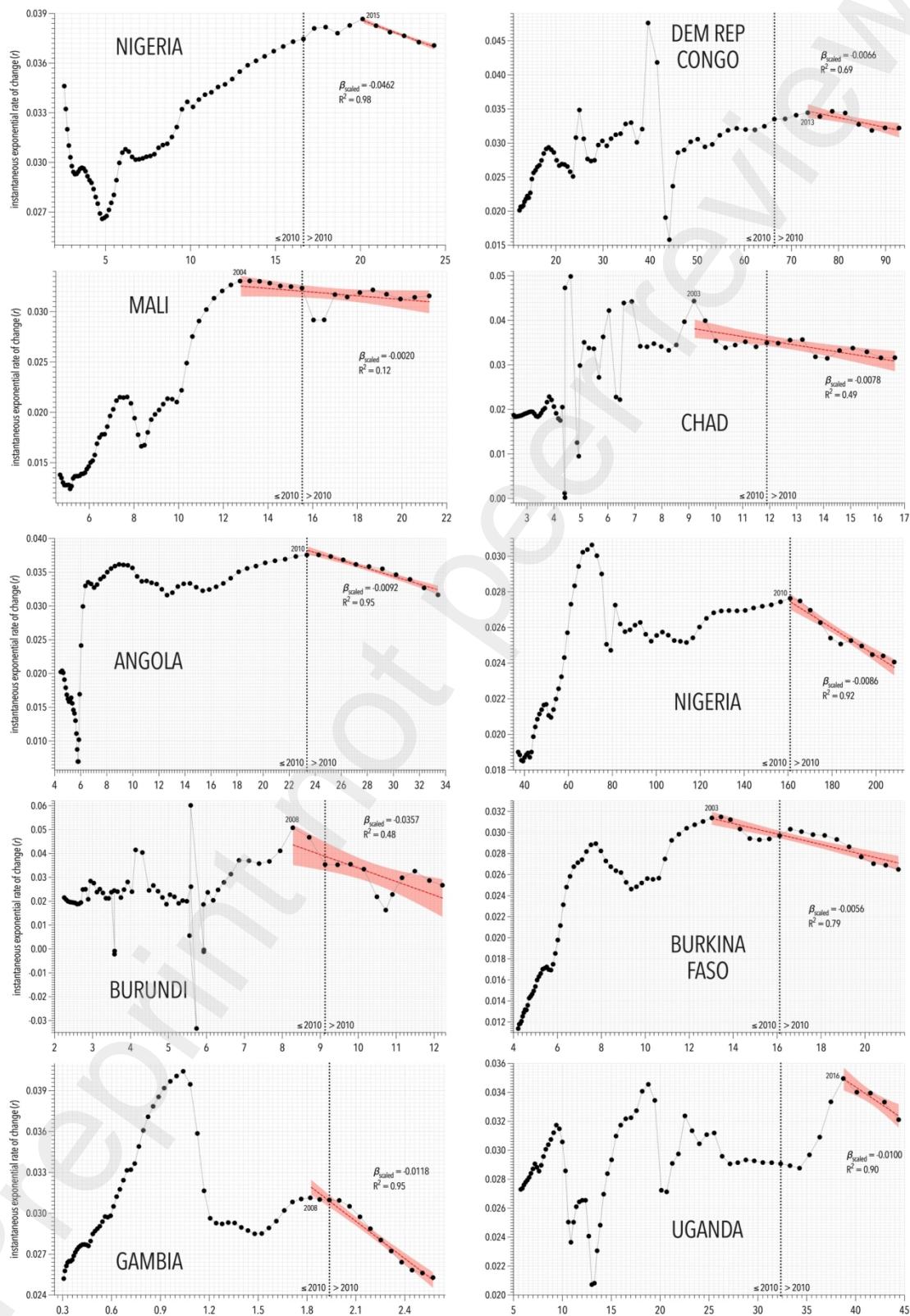
786 **Figure S2.** Resampled (10,000 iterations) slope β , where more negative values indicate increasing rate of
787 decline in the instantaneous exponential rate of annual growth ($r = \log_e(N_{t+1}/N_t)$ relative to population size (N ,
788 scaled, but not centred, using the *scale* function in R to ensure $\hat{\beta}$ are on the same scale) at time t per major
789 global region from 1950–2023. Error bars indicate 95% confidence intervals. Regions ordered from most
790 negative β to least negative β . See also Fig. 3.



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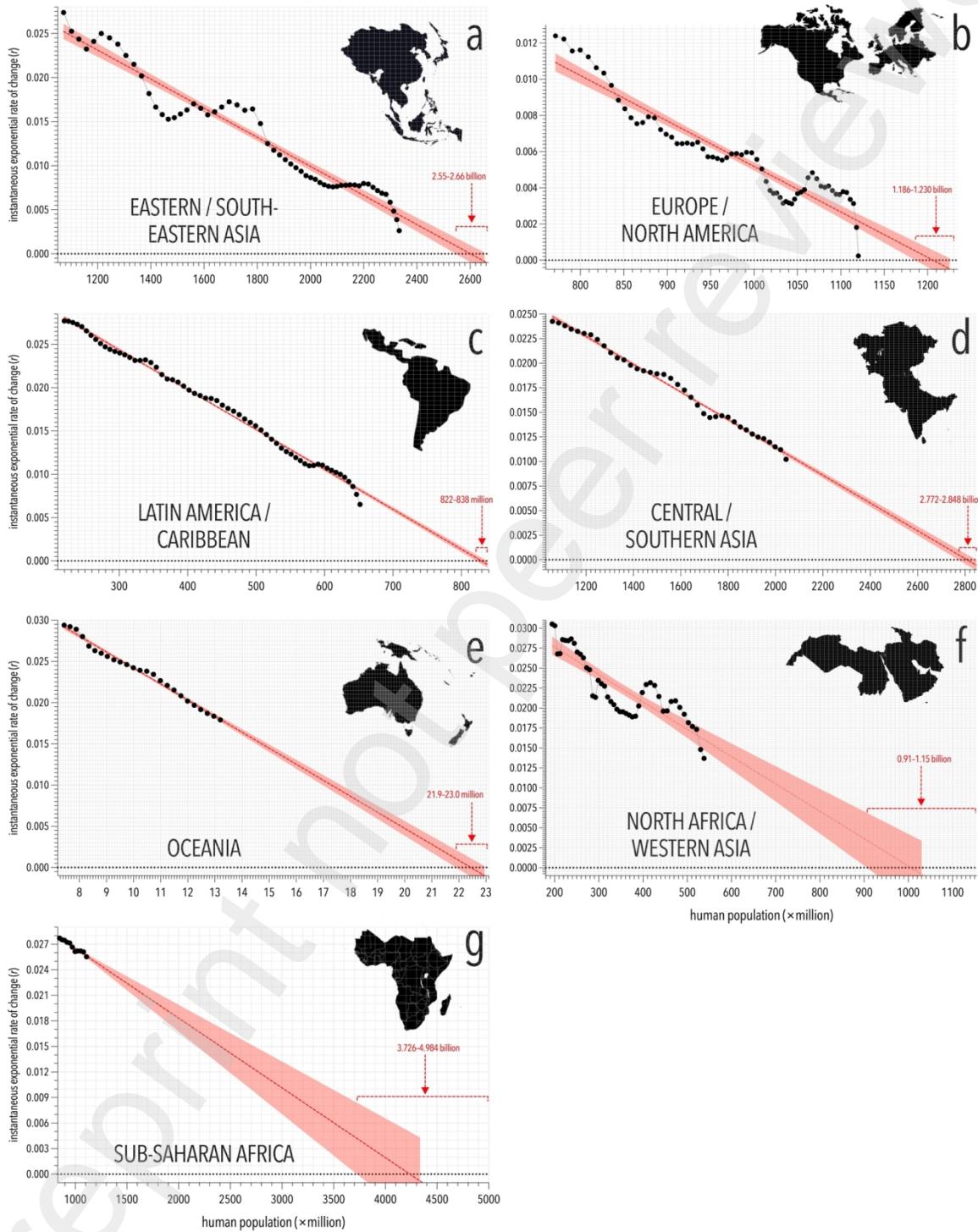
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Figure S3. Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and population size (N) at year t from 1950 to 2023 for the ten countries with the highest current fertilities globally (Niger, Democratic Republic of Congo, Mali, Chad, Angola, Nigeria, Burundi, Burkina Faso, Gambia, Uganda; data.worldbank.org). N for each are first scaled so that slopes are on the same scale. Vertical dotted line in each panel indicates the onset of the negative phase (> 2009) from the combined dataset for Sub-Saharan Africa (Fig. 3). The year when the negative phase began in each country shown in each panel. Red shading indicates 95% confidence interval of the Ricker logistic fit.



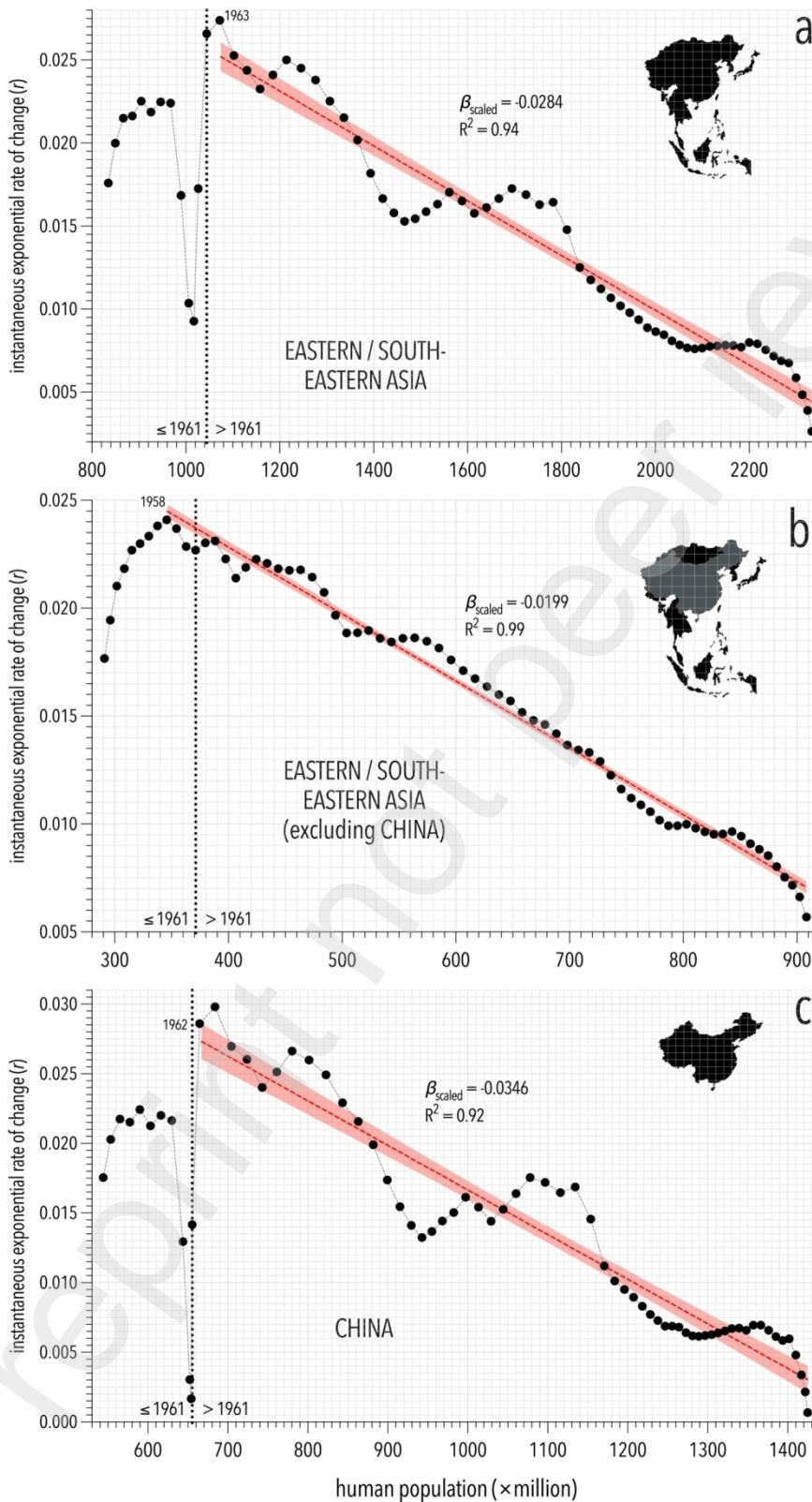
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801 **Figure S4.** Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and
802 population size (N) at year t for the negative phase only for seven major global regions, sorted by descending
803 magnitude of slope (rate at which r declines with N). (a) eastern and south-eastern Asia, (b) Europe and North
804 America, (c) Latin America and Caribbean, (d) central and southern Asia, (e) Oceania, (f) northern Africa and
805 western Asia, (g) Sub-Saharan Africa. For each region, the relationship is extended to $r = 0$ as an estimate of
maximum regional population size (K_m). See also Fig. 3.



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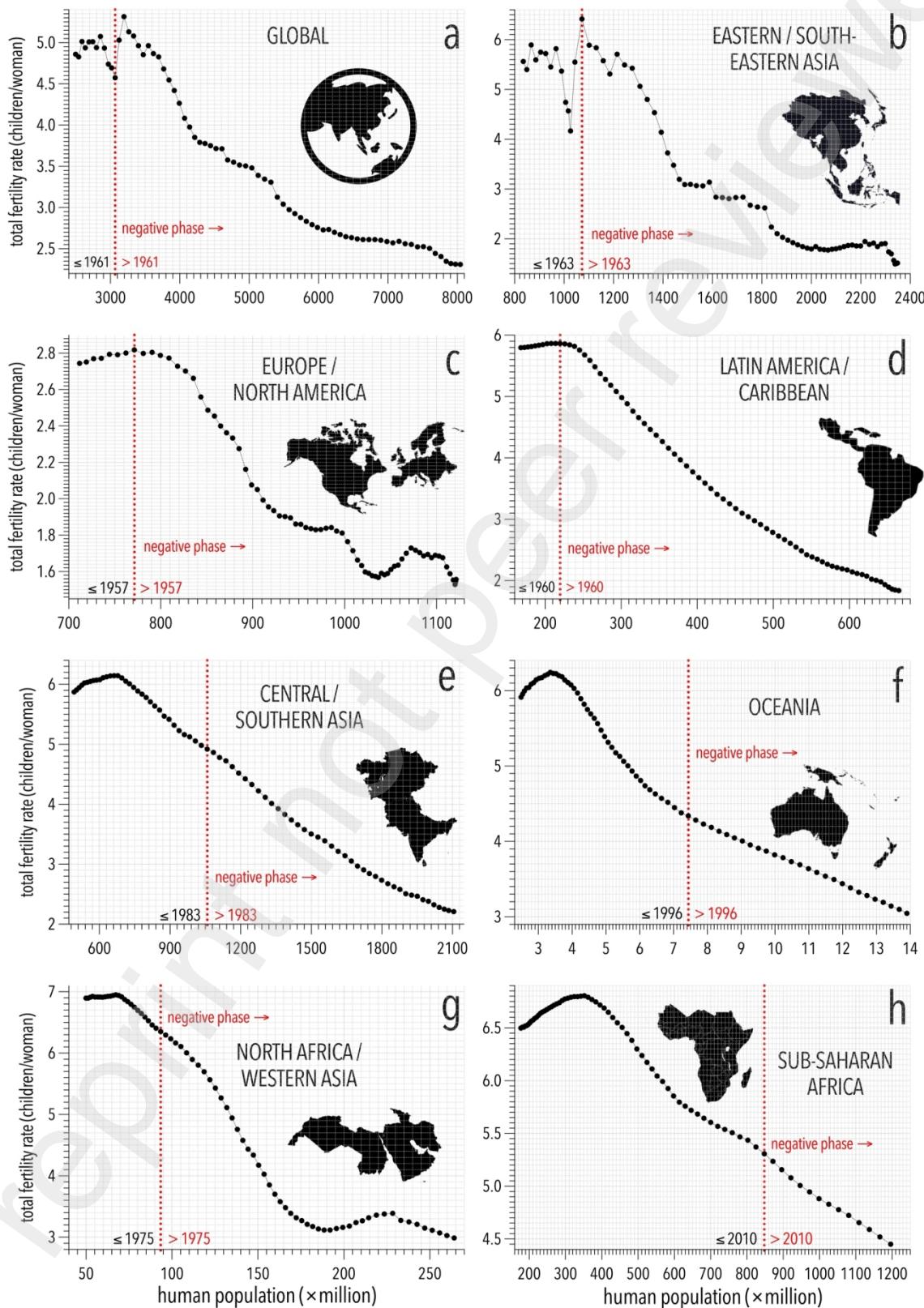
807 **Figure S5.** Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and
 808 population size (N) at year t from 1950 to 2023 for (a) eastern and south-eastern Asia, (b) eastern and south-
 809 eastern Asia excluding China, and (c) China. N for each are first scaled so that slopes are on the same scale.
 810 Vertical dotted line in each panel indicates onset of the negative phase (> 1961) from the global data (Fig. 2).
 811 The year when the negative phase began in each region shown in each panel. Red shading indicates 95%
 812 confidence interval of the Ricker logistic fit.



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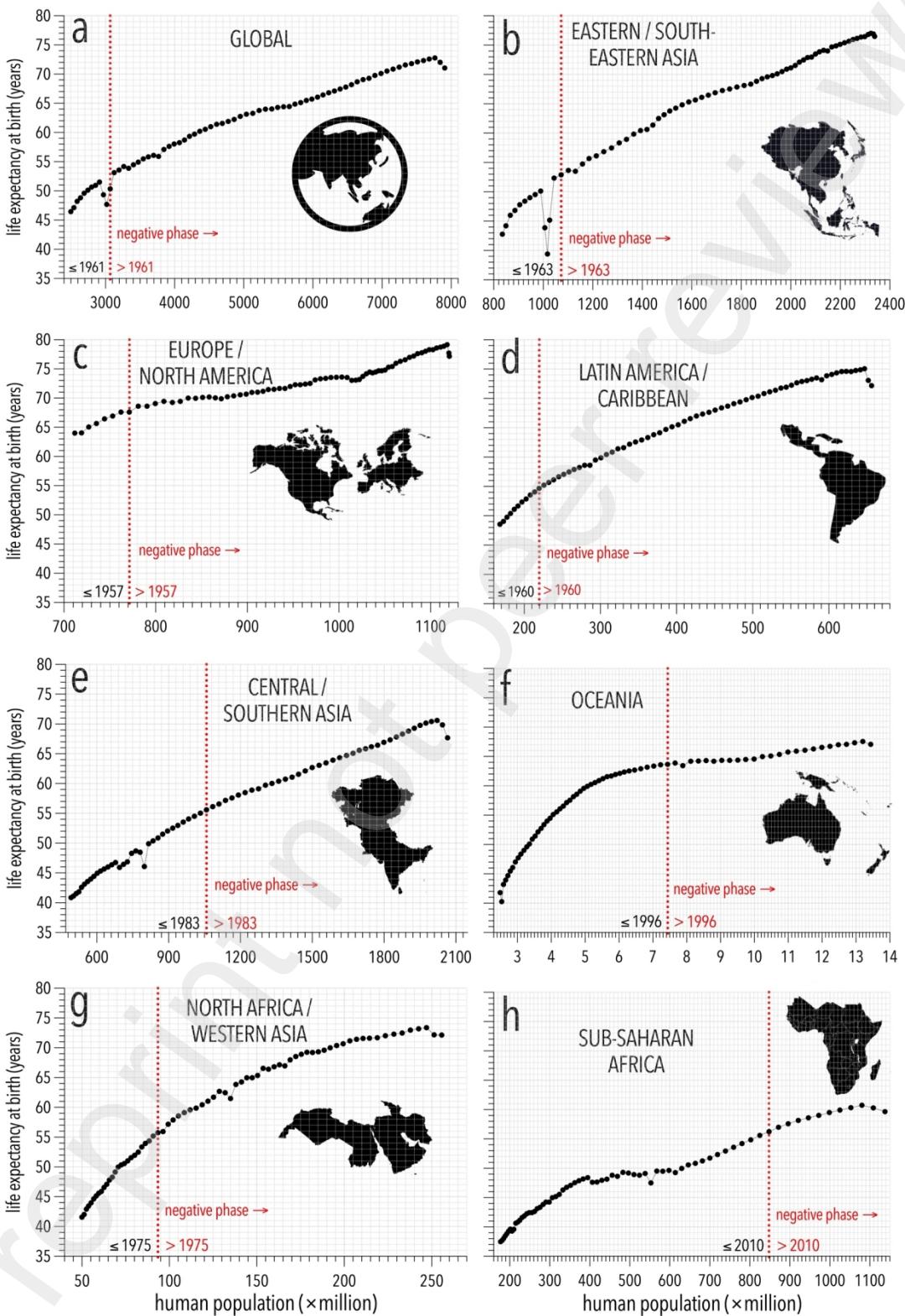
Figure S6. Relationship between total fertility rate (children/woman) and population size (N) from 1950–2023 for (a) the entire globe + (b–h) seven major global regions: (b) eastern and south-eastern Asia, (c) Europe and North America, (d) Latin America and Caribbean, (e) central and southern Asia, (f) Oceania, (g) northern Africa and western Asia, (h) Sub-Saharan Africa. The onset of the negative $r \sim N$ phase is shown as a vertical red dotted line in each panel (see Fig. 2 and 3).



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Figure S7. Relationship between life expectancy at birth (years) and population size (N) from 1950–2021 for (a) the entire globe + (b–h) seven major global regions: (b) eastern and south-eastern Asia, (c) Europe and North America, (d) Latin America and Caribbean, (e) central and southern Asia, (f) Oceania, (g) northern Africa and western Asia, (h) Sub-Saharan Africa. The onset of the negative phase is shown as a vertical red dotted line in each panel (see Fig. 2 and 3).



825

826 **Appendix III. Predictors of global temperature anomaly**

827
828 To examine the relative contribution of human population size (N) and per-capita energy
829 consumption⁸³ (E) on the global temperature anomaly (TA) (Fig. S8), we compared four
830 linear models with different combinations of the two predictors: $TA \sim N+E$, $TA \sim N$, $TA \sim E$, and
831 the intercept-only model. Because the response variable TA has associated confidence
832 intervals, we resampled the values uniformly between the upper and lower 95% confidence
833 limits, and then resampled the entire dataset ($n = 30$ sampled values) with replacement to
834 limit the effect of temporal autocorrelation. To each resampled dataset, we applied the same
835 four linear models and iterated 10,000. We then calculated the proportion of those iterations
836 each model was the highest ranked according to the weight of Akaike's information
837 criterion⁷⁰ corrected for small samples ($wAIC_c$), the median $wAIC_c$, and the median
838 percentage of deviance explained for each model.

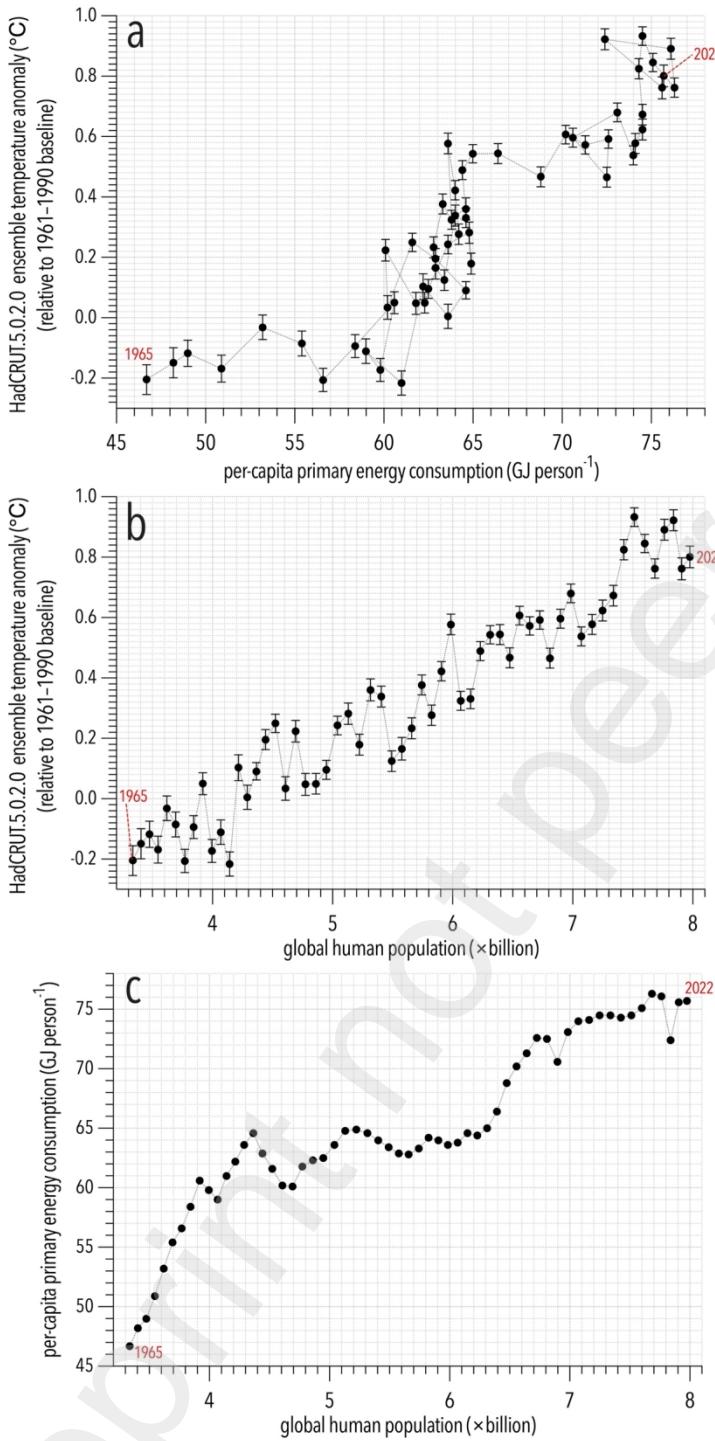
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840 Over the 10,000 iterations, population size (N) was the dominant model (highest-ranked
841 89.5% of all iterations; median $wAIC_c = 0.712$, equivalent to model probability; explaining
842 68% of the deviance; Table S1). The model including both N and per-capita energy
843 consumption (E) was highest-ranked 13.1% over all iterations, but because N and E are
844 moderately collinear (variance inflation factor = 7.59), the $N+E$ model explains < 2%
845 additional deviance (Table S1). We conclude therefore that N is more influential on
846 temperature anomaly than E , in agreement with previous analyses^{84,85}.

847
848 **Table S1.** Linear model comparison results for predicting the global temperature anomaly (TA) with human
849 population size (N) and per-capita energy consumption (E). **prop top** = proportion of 10,000 iterations where
850 model was highest ranked; **median wAIC_c** = median weight of Akaike's information criterion corrected for
851 small samples; **median %DE** = median % deviance explained by the model.

model	prop top	median wAIC _c	median %DE
$TA \sim N$	0.895	0.712	67.9
$TA \sim N + E$	0.131	0.286	69.4
$TA \sim E$	0.001	0.002	51.8

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855 **Figure S8.** (a) Relationship between global temperature anomaly ($^{\circ}\text{C}$) derived from the HadCRUT.5.0.2.0
 856 ensemble model⁶⁹ compared to the 1961–1990 baseline and per-capita annual primary energy consumption⁸³
 857 from 1965 to 2022 (36). (b) Relationship between global temperature anomaly and human population size. (c)
 858 Relationship between per-capita energy consumption and human population size.



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 861 We also designed a randomised boosted regression tree⁸⁶ routine to test the relative influence
 862 of both N and E on TA , because machine-learning algorithms like random forest and boosted
 863 regression trees are generally insensitive to collinearity^{86–89}. To reduce the potential influence
 864 of temporal autocorrelation, we first resampled the dataset with replacement, and then
 865 resampled the TA in that resampled dataset uniformly between the upper and lower 95%

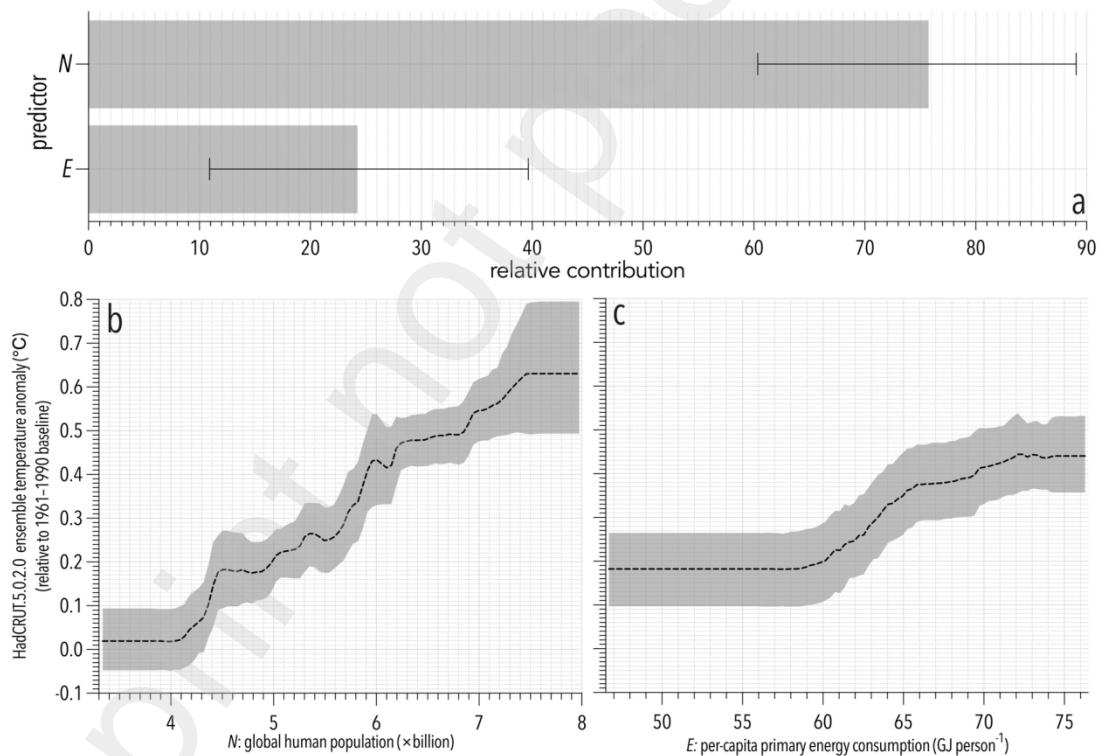
confidence limits as in the linear model approach described above. To each resampled dataset, we fit a boosted regression tree algorithm using the `gbm` library⁹⁰ in R with a bag fraction = 0.75, a tree complexity = 2, a learning rate = 0.001, and a tolerance = 0.0001. After 1000 resampling iterations, we calculated the 2.5th and 97.5th percentiles for the respective distribution for each predicted *TA* as the uncertainty bounds. We applied a kappa (κ) limitation to the resampled selections to limit the influence of outliers, where we retained only the resampled mean ranks within $\kappa\sigma$ of the overall average mean ($\kappa = 2$). We then recalculated the average and standard deviation of the mean rank, repeating the process five times.

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The results confirmed the dominant influence of global population size (*N*) on the temperature anomaly (*N*) (Fig. S9a) — temperature anomaly increased monotonically with both increasing population size (Fig. S9b) and per-capita primary energy consumption (Fig. S9c).

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Figure S9. (a) Relative contribution of global population size (*N*) and per-capita primary energy consumption (*E*) on the global temperature anomaly. Error bars represent 95% confidence bounds after 1000 resampling iterations. Overall, the boosted regression tree predictors explained 93.5% to 97.8% (coefficient of variation) of the variance in the global temperature anomaly. (b) Predicted relationship between temperature anomaly and global human population size from the 1000 resamples of the boosted regression trees. (c) Predicted relationship between temperature anomaly and per-capita primary energy consumption from the 1000 resamples of the boosted regression tree.



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