ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Global human population has surpassed Earth's sustainable carrying capacity

To cite this article: Corey J A Bradshaw *et al* 2026 *Environ. Res. Lett.* **21** 064023

IOP Publishing Environ. Res. Lett. 21 (2026) 064023 https://doi.org/10.1088/1748-9326/ae51aa

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
14 October 2025

REVISED
7 February 2026

ACCEPTED FOR PUBLICATION
13 March 2026

PUBLISHED
27 March 2026

LETTER

Global human population has surpassed Earth's sustainable carrying capacity

Corey J A Bradshaw[1,2,*], **Melinda A Judge**[3,4], **Daniel T Blumstein**[5,6], **Paul R Ehrlich**[7,12], **Aisha N Z Dasgupta**[8,11], **Mathis Wackernagel**[6,9], **Lewis J Z Weeda**[10] **and Peter N Le Souëf**[10]

[1] Global Ecology | Partuyarta Ngadluku Wardli Kuu, College of Science and Engineering, Flinders University, GPO Box 2100, Adelaide, South Australia 5001, Australia
[2] Australian Research Council Centre of Excellence for Indigenous and Environmental Histories and Futures, Cairns, Queensland, Australia
[3] The Kids Research Institute Australia, Perth, Western Australia, Australia
[4] School of Mathematics and Statistics, University of Western Australia, Nedlands, Western Australia, Australia
[5] Department of Ecology and Evolutionary Biology, University of California, Los Angeles, Los Angeles, CA, United States of America
[6] Institute of the Environment and Sustainability, University of California, Los Angeles, CA, United States of America
[7] Department of Biology, 327 Campus Drive, Stanford University, Stanford, CA 94305, United States of America
[8] UK Foreign, Commonwealth and Development Office, King Charles Street, London, SW1A 2AH, United Kingdom
[9] Global Footprint Network, Oakland, CA, United States of America
[10] School of Medicine, University of Western Australia, Nedlands, Western Australia, Australia
[11] Current address: Judge Business School, University of Cambridge, Cambridge CB2 1AG, United Kingdom.
[12] Deceased.
[*] Author to whom any correspondence should be addressed.

E-mail: corey.bradshaw@flinders.edu.au

Keywords: carrying capacity, climate change, consumption, population growth, temperature anomaly

Supplementary material for this article is available online

Abstract

The ecological concept of human carrying capacity is necessarily complicated because human beings are the 'ultimate ecosystem engineers' who moderate the environment for their benefit. For at least the last few hundred years, human ingenuity, access to massive stocks of fossil fuels, and technological development have driven facilitation whereby increasing human abundance has promoted higher population growth rates. However, this positive relationship broke down during the 1950s, and by 1962, the global human population entered a phase where the growth rate consistently declined as population increased. The onset of this negative phase occurred 8 years before a global biocapacity deficit began in 1970. The onset of the negative phase also varies regionally, with the lowest-income and highest fertility regions entering this phase later than higher-income regions. A Ricker logistic model fitted to the negative phase predicts that the global population could reach 11.7–12.4 billion people between 2067 and 2076. The same model fitted to the facilitation phase predicts a maximum population of 2.5 billion people that Earth might be able to maintain. The negative phase also correlates strongly with the trend in global temperature anomaly, ecological footprint, and total emissions, with more of their variation explained by increasing population size rather than increasing per-capita consumption. The Earth cannot sustain the future human population, or even today's, without a major overhaul of socio-cultural practices for using land, water, energy, biodiversity, and other resources.

1. Introduction

Human beings undoubtedly have the best-studied demography of any species, yet for most of human existence, there were no accurate censuses of population size, nor estimates of age structure, birth, or death rates. However, since the 1950s when global population censuses began in earnest [1], we now have an in-depth appreciation for how population structure has changed in response to shifting economics [2], social dynamics [3], education [4], culture [5, 6], health interventions [7, 8], family planning [2, 9], marriage patterns [10], migration [2, 11], warfare [12], and disease [13], among others. Yet despite the wealth of data and analyses on human demography, we still have a poor understanding of how the global human population might respond to its own processes of self-facilitation and limitation within the constraints of environmental feedbacks [2], especially considering we have data for only a tiny fraction of the history of *Homo sapiens*. Additionally, the demography-environment nexus is generally under-developed in the field of human demography [14–16], despite environmental variation being one of the principal mechanisms determining patterns of human demographic change [14].

Carrying capacity is an ecological concept describing the long-term average maximum number of individuals of a particular species (typically measured as a density in individuals per unit area and denoted K) an environment can sustain indefinitely given the available regenerative resources [17–19]. In mathematical terms, K can be calculated as the long-term mean population size (N) where the *per capita* rate of exponential population change (r) approaches zero [17, 18] (supplementary material appendix I, figure S1). This phenomenological relationship is the *ensemble* expression of *component* feedback [20]—the process by which interactions among individuals and groups affect component demographic rates (e.g. survival, fertility, and dispersal). Variation in the components in turn 'feed back' directly or indirectly to alter population size and the demographic rates themselves [21]. There are two main types of phenomenological relationship between r and N—*negative*, where the rate of population growth declines as population size increases, and *facilitation*, a special case where the rate of population growth rises as the population increases [21].

Applied to human populations, the concept of carrying capacity is necessarily complicated because human beings are the 'ultimate ecosystem engineers' who deliberately and successfully moderate the environment for their benefit [22, 23]. In contrast to non-human species limited by the regenerative resource base on which they depend directly, modern humans have essentially eradicated the limiting feedback from resource depletion via the exploitation of fossil fuels. Other reasons why the concept of ecological carrying capacity applied to human populations is cumbersome is because of the huge variation in the amount of resources used and environmental damage caused by individuals [24], the access to non-renewable stocks of resources that can complement regenerative resources, and the difficulty in determining what technological innovations and standards of living are considered 'acceptable' [22] at any given population size and fertility rate. The latter reason is possibly the most intractable element when applying carrying capacity to human beings, because K has different interpretations depending on the economic system and technologies at play, whether societies endeavor to reduce inequality, over what period of time one decides to apply the criteria, how much environmental damage we are willing to endure or accept [23, 25], and at which point the environmental damage is so great and the human load so high that those physical conditions start to limit the size of human populations directly. In addition, Rees [26] argued that technological innovation often does not increase K *per se*, but only the efficiency of resource use, which can create the illusion of increase while shielding people from perceiving the permanent damage to the resource base.

Another complication is that despite the well-documented, planetary-wide ecological and extinction crisis underway [22, 27, 28] made possible by the exploitation of fossil fuels, and the observation that human societies have long ago exceeded the Earth's 'biocapacity' (i.e. the productivity of ecological assets, including cropland, grazing land, forest land, fishing grounds, and built-up land) [29], gross measures of human wellbeing are generally at historical highs; for example, absolute poverty is declining [30] (although country-specific poverty is rising) [30], as is child mortality [31], while longevity is mostly increasing [32]; however, longevity has potentially been reduced by the effects of COVID-19, under-nutrition has increased [33] by ∼30% between 2017 and 2021, and obesity is rising [32]. This apparent paradox has come at a cost to the stability of humanity's life-support system, and a massive increase in dependence on fossil fuels, which is in turn threatening the very life-support system that sustains this population via resultant climate change, while also blinding societies to finite, regenerative biological resources as long as fossil fuel-based alternatives are available. The pressures on the biosphere also stem from persistent overuse, including past carbon emissions. This means that the stressors are the outcome of cumulative, historical overuse, not just current activities. Together, these stressors limit continued improvement, and are instead likely to or have already started to reduce standards of living [27, 34].

As a result, there have been many scientific discussions of human carrying capacity [19, 22–25, 35–37], with no clear consensus on either its value [23] or even relevance to modern human society. However, most appear to agree that for human beings, 'optimum' carrying capacity is considerably lower than 'maximum' (or 'biophysical') carrying capacity [24, 25, 37]. The qualifier 'optimum' appears to refer to a feedback connected to an enhancement of well-being via socio-economic development and environmental integrity [22], such as the maximum number of people that can be sustained at a minimum standard of living [36, 37], rather than a maximum density dictated instead by famine, disease, and war [35].

To address the lack of evidence-based estimates of human carrying capacity and the role of population itself in affecting future human growth, we calculate using well-established demographic analyses from ecology both a realistic 'facilitation' (~2.5 billion) and maximum (11.66–12.40 billion) global population size from the available data describing trends in human abundance estimates over the last century. Our predictions are the first to be based on human population time series alone, because no previous study has investigated the evidence for relationships between r and N at the global or regional scales. Such an investigation is important not only to calculate empirical estimates of carrying capacity that do not rely on unjustified or uncertain assumptions underlying existing estimates of carrying capacity [23], but also to identify whether population growth rates have shifted in response to dwindling per-capita resources and potential negative feedbacks from over-consumption.

Using population data from the United Nations and other sources back to 1800, we show empirically that human societies shifted from a long period of facilitation (i.e. more people = higher instantaneous exponential rate of annual increase) at the end of the 1940s, to one where further increases in population size were associated with consistently declining growth rate beginning in the 1960s (negative phase). Further, we show for the first time that the global temperature anomaly, ecological footprint, and total emissions (indices of global environmental deterioration) increased monotonically with increasing population size during the most recent negative phase, and that population size is a stronger predictor of the variation in the indices of global change than rising per-capita consumption rate.

2. Methods

2.1. Population trend and rate of change

We compiled the available estimates of human population size back to 1000 AD, given that the period since then includes estimates corroborated by several independent analyses [1, 38–46]. From these data, we calculated the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$) and population size (N) at year t from 1800 to 2023 (because global population sizes are available in annual increments during that period) [44].

We calculated the linear relationship between the annual exponential rate of change (r) and global population size (N) based on the phenomenological 'Ricker' (linear) [47] and 'Gompertz' (log-linear) [48] logistic models [20] in *R* (function: *lm*). We contrasted the relative fits of the Ricker and Gompertz logistic models using Akaike's information criterion weights ($w\text{AIC}_c$). However, these calculations of r are not accompanied by any measured uncertainty provided by the United Nations. Comparing historical revisions with projections between 1970 and 2020 reveals only a modest (1%–2%) discrepancy, an uncertainty that agrees well with the ~1% variation observed among estimates from different sources [49]. There is also evidence that the uncertainty around population size estimates for different regions also varies, but that uncertainty generally declines over time [50]. To test whether the trends we observed between r and N_t in the three phases (see Results) are robust in the face of uncertainty, we designed a resampling approach where we assumed uncertainties around annual N_t of 5% for the facilitation phase (1800–1949), 2% for the transition phase (1950–1961), and 1% for the negative phase (1962–2023). For each of 10 000 iterations, we sampled a random deviate uniformly within these error ranges for each N_t in the series, recalculated the corresponding r, and then calculated the slope of the least-squares linear relationship between r and N_t for each phase.

2.2. Carrying capacity

A phenomenological Ricker logistic model [20] predicts that when a population's $r = 0$ (stability, or zero population 'growth'), the quotient of the negative intercept and slope of the linear fit of $r \sim N_t$ estimates an expected 'maximum' population size (which we term 'Ricker carrying capacity', K_R). This is distinct from a ('biophysical') [37] carrying capacity of the environment [24], which would be a population size that could be sustained, and would not just operate on stock depletion as it does currently. This population K_R is reached at the point when total births are perfectly offset by total deaths. As additional reality checks of the relationships, we extended the Ricker logistic model to the intercept (where $N_t = 0$) to calculate the theoretical maximum rate of increase [51]. Likewise, extending the facilitation relationship back to $N_t = 0$ we calculated the expected r_m for 'undeveloped' societies in the absence of facilitation [52].

A 'sustainable' carrying capacity' is considerably lower than a 'maximum' population size predicted at $r = 0$ using the Ricker model (K_R) [24, 25, 37]. This is because K_R is enabled by stock depletion, which allows people temporarily to overcome the limitations imposed by the regeneration rates of biological resource supplies. The 'sustainable' carrying capacity also depends on the average standard of living per individual. The higher the consumption per person, the lower the 'sustainable' carrying capacity. A world with a human population at a 'sustainable' carrying capacity is better than one at K_R, because the former population size is more likely to provide more stable economies, have lower negative environmental impacts, endure longer, have fewer risks, and maintain more cultures and values [25, 53]. Given the evidence for an abrupt switch from facilitation to a negative $r \sim N$ phase (see Results), we calculated this lower carrying capacity as the population size where facilitation produced maximum r (henceforth denoted K_f). Here, we calculated the global population size when r was maximum during the 1800–1949 facilitation as K_f.

2.3. Regional differences

Treating the global population as a single unit potentially masks regional differences in the onset and strength of the negative relationship between r and N. As a form of sensitivity analysis to confirm that the global trend was not driven by particular regions and/or countries, we therefore divided the globe into seven main regions defined by the United Nations (Sub-Saharan Africa, northern Africa and western Asia, Europe and North America, Latin America and Caribbean, central and southern Asia, eastern and south-eastern Asia, and Oceania [+ Oceania excluding Australia and New Zealand]) and calculated the $r \sim N$ relationship for each. We also extended the fits to $r = 0$ for each region's negative phase to provide an estimate of K_R for each, and examined the regional differences in slope of $r \sim N$ relative to several demographic and economic indicators (supplementary material appendix IV).

2.4. Correspondence to projections

We plotted the global prediction of K_R from the Ricker logistic model applied to the negative phase (figure 2(b)) against the most-plausible [31] projections of human population size to the end of this century (United Nations Population Division *Medium, High*, and *Probabilistic* scenarios) [1], and the International Institute for Applied Systems Analysis and the European Commission's Joint Research Centre [IIASA-JRC] *Stalled* and *Reference* scenarios [54, 55]. This approach identifies which projections have the best correspondence to the magnitude and timing our calculated K_R from the Ricker-logistic model.

2.5. Indices of global change

We compared global human population size in the three main phases of facilitation, transition, and the negative $r \sim N$ phase (see Results) to the global temperature anomaly obtained from the HadCRUT.5.0.2.0 ensemble prediction anomaly [56] relative to the 1960–1991 baseline (data available from 1850 to the present). We hypothesize that the strongest positive relationship between human population size and climate change occurred during the negative phase because of consumption externalities such as increasing natural resource exploitation and loss of biodiversity. This can result from societies in the period of declining r and resources subsequently driving environmental degradation. In contrast, societies in the facilitation phase might have adequate resources to fuel increasing population growth rates. We also used two additional indices of global change in the analyses to corroborate the results using global temperature anomaly: global ecological footprint measured as the number of Earths required to meet consumption rates [29], and total annual CO_2-e emissions (ourworldindata.org). See the supplementary material appendix III for the full methodology. All code and data underlying all analyses are available at https://doi.org/10.5281/zenodo.10951676.

3. Results

3.1. Population trend and rate of change

The trajectory of the global human population slowly increased (mean $r = 0.0009$) from an estimated 323 million in 1000 CE to 592 million in 1700 (figure 1(a)). From the onset of the Industrial Revolution in the mid-18th Century, the calculated rate of increase expanded considerably (mean $r = 0.005$, or 5 times the rate observed between 1000 and 1700 CE) to produce a global population of 985 million by 1800 (figure 1(a)). Population increase was consistently positive thereafter, despite at least 27 major mortality events (each with $\geqslant$1 million estimated casualties counted as excess deaths), four of which had $\geqslant$30 million casualties each—i.e. Taipeng rebellion (Platt 2012), 'Spanish' influenza pandemic [57], World War II [58], and the Chinese famine [59] (figure 1(b)). Following World War II when global population censuses began in earnest [1], we calculated that the global human population expanded at its fastest rate ever [2], reaching an average rate of increase of $r = 0.02$ between 1950 and 1970. This increase is known as the post-World War II Baby Boom of the 1950s and 1960s (figure 1(b)).

The linear relationship between the annual exponential rate of change (r) and global population size (N) shows a striking shift during the 1950s from facilitation (positive) to a negative phase (figure 2). From 1800 to 1949, there was a clear signal of facilitation—population growth rate increased with increasing global population size [21]. Here, the 95% confidence interval of the Ricker slope (β) was 0.0033–0.0046 ($R^2 = 0.488$). There was dominant support for the Ricker ($w\text{AIC}_c = 0.828$) relative to the Gompertz model ($w\text{AIC}_c = 0.172$; evidence ratio $= w\text{AIC}_{c\,[\text{Ricker}]}/w\text{AIC}_{c\,[\text{Gompertz}]} = 4.83$). There was a weak autocorrelation signal in the r time series for the facilitation phase (partial autocorrelation function showed evidence for a lag effect = 1 year; supplementary material appendix II figure S2), with a Newey–West correction for autocorrelation returning a slope of $\beta = 0.0024$–0.0055. This means that

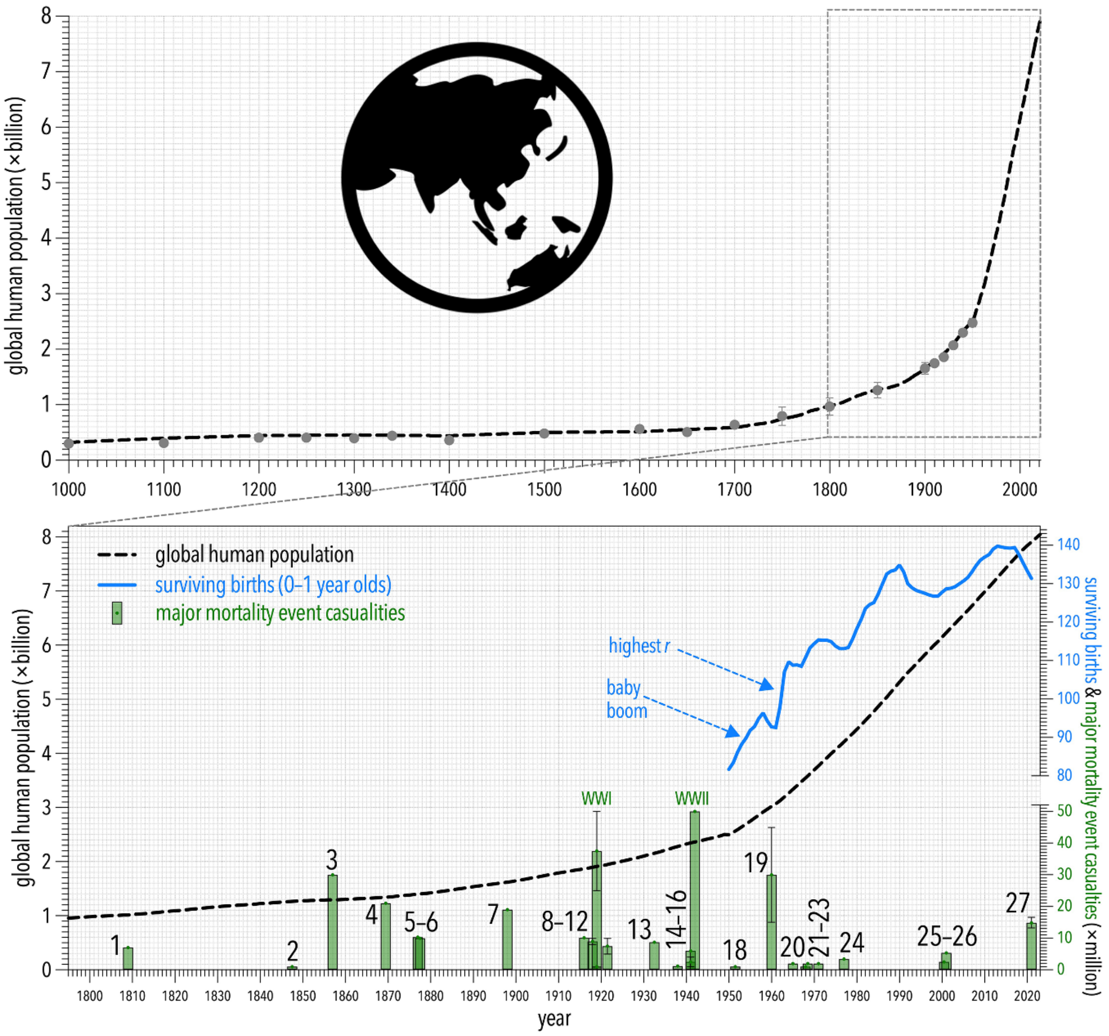

Figure 1. Global human population size from 1000 to present (main figure) and from 1800 to present [1, 40, 42, 44] (black line; inset). Dark gray circles with confidence limits derived from the upper and lower estimates of several sources [38, 39, 41, 43, 45, 46]. Inset shows approximate magnitude (green bars; casualties) of major human mortality events (with ⩾ 1 million deaths) since 1800 (right *y* axis; green; see references below figure for sources).
Mortality events listed: 1. Napoleonic wars (7 million) [60], 2. Irish famine (1 million) [61]; 3. Taiping rebellion (30 million) [62], 4. Dungan revolt (21 million) [63], 5. British India famine (10.3 million) [64], 6. Northern Chinese famine (10 million) [65], 7. Indian famine (19 million) [66], 8. World War I (10.1 million) [58], 9. Iranian famine (8–10 million) [67], 10. Influenza pandemic (25–50 million) [57], 11. Russian civil war (1 million) [58], 12. Russian famine (5–10 million) [68], 13. Soviet famine (8.7 million) [69], 14. Chinese civil war (1.2 million) [58], 15. 2nd Sino-Japanese war (1–4 million) [58, 70] and 16. Famine (6 million) [70], 17. World War II (50 million) [58], 18. Korean war (1 million) [58], 19. Chinese famine (15–45 million) [59], 20. Vietnam war (2 million) [58], 21. Nigerian civil war (1 million) [71] and 22. Famine (2 million) [72], 23. Chinese Cultural Revolution (2 million) [58], 24. Cambodian genocide (3.4 million) [73], 25. 2nd Congo civil war (2.5 million) [74] and 26. Famine (5.4 million) [75], 27. COVID-19 (13.23–16.58 million) [76].

per-capita fitness (survival, reproduction) increased as the population increased (i.e. facilitation), implying self-reinforcement via technological and socio-economic improvements to living conditions [22].

The post-WWII Baby Boom during the 1950s precipitated a large increase in the growth rate, but de-stabilized the relationship between r and N_t (the negative r calculated for 1949–1950 is an artefact of global census data being standardized from 1950 onward—the human population did not decrease during this period and then recover in one year; we removed this value from Ricker model estimates). We found no relationship between r and N_t according to the linear model ($\beta = -0.0102$–0.0047), with a Newey–West correction for autocorrelation giving $\beta = -0.0109$–0.0054. However, by 1961, the global human population became locked into a negative phase (the highest-recorded r was from 1962–1963; figure 2(a)), whereby further increases in the population were accompanied by decreasing population growth rate ($\beta = -0.0025$ to -0.0023; $R^2 = 0.952$; figure 2(a)). There was nearly no support for the Gompertz model ($w\text{AIC}_c = 0.00052$; evidence ratio of Ricker relative to Gompertz = 1971.6). There was a modest autocorrelation signal in the r time series for the negative phase (partial autocorrelation function showed evidence for a lag effect of 1 and 2 years; supplementary material), with a Newey–West

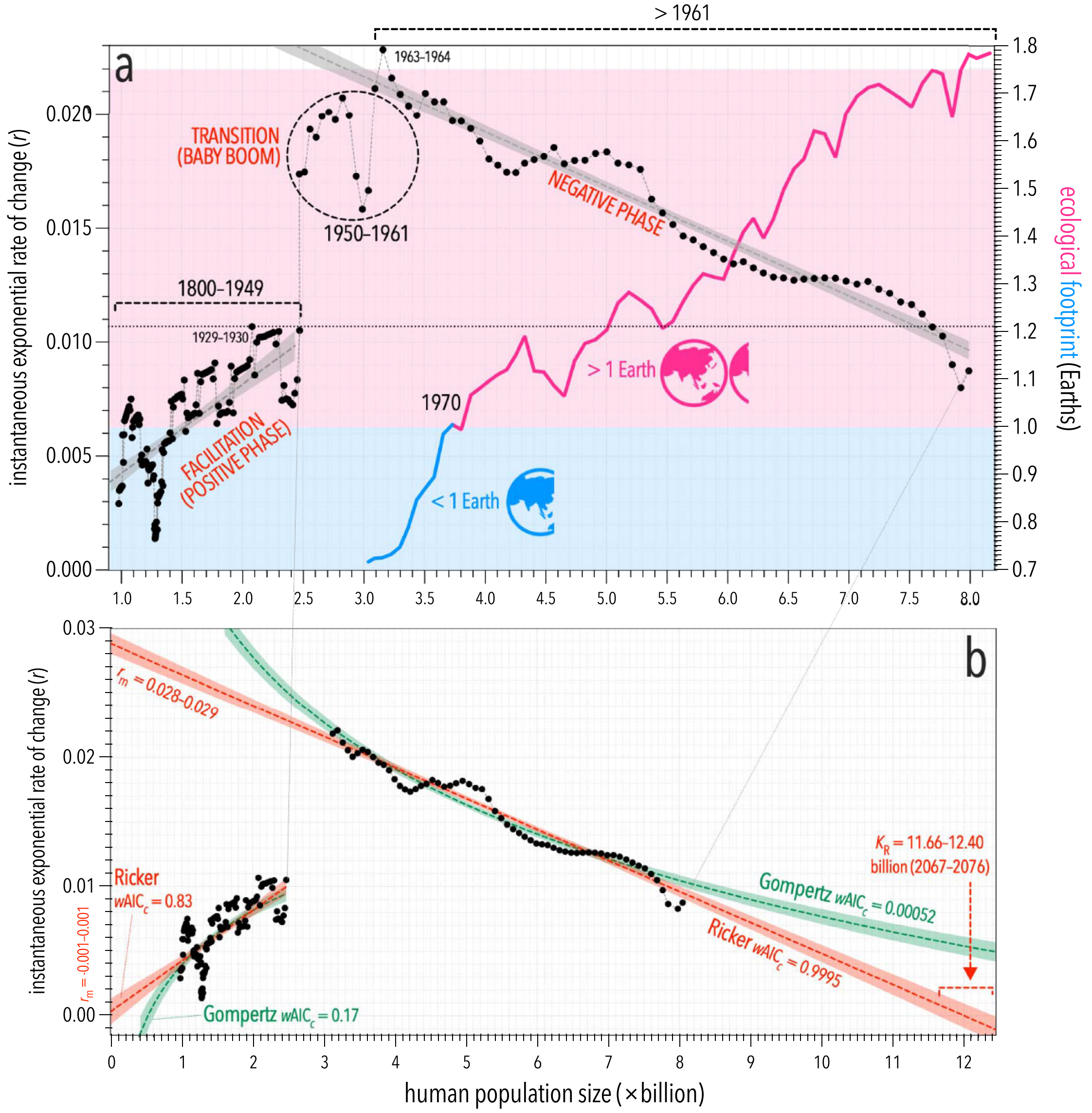

Figure 2. (a) Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$ and population size (N) at year t from 1800 to 2023. There is a positive relationship between r and N_t from 1800 to 1949, indicating facilitation. The dotted horizontal line intersecting 1929–1930 indicates the highest r observed during the facilitation phase (0.011). The negative r shown for 1949–1950 is an artefact of global census data being standardized from 1950 onward. However, following WWII through the 1950s, there was a period of transition toward high r, but no relationship with N_t, and then the establishment of a negative $r \sim N_t$ relationship from around 1961–1962 to the present. Also shown on the right y axis is the ecological footprint expressed in terms of number of Earth's required to meet global human consumption—at 1 'Earth', the global ecological footprint (ecological assets the global population requires to produce the natural resources it consumes and to absorb its wastes) equals the Earth's biocapacity (productivity of ecological assets, including cropland, grazing land, forest land, fishing grounds, and built-up land) [29]. The global ecological footprint has exceeded the Earth's biocapacity since 1970 (transition from blue to pink). (b) Ricker and Gompertz logistic relationships for the facilitation and negative phases (Akaike's information criterion weights $w\text{AIC}_c$ shown for each model for each phase) indicate most support for the Ricker model. Extending the fitted Ricker relationship between r and N_t to where r (y) = 0 indicates maximum (biophysical) global population size (K_R = −intercept ÷ slope). Assuming no deviation from this expected relationship, $K_R = 11.66–12.40$ billion people predicted to occur between 2065 and 2074. Extending the negative relationship back to N_t (x) = 0 (intercept) indicates the theoretical maximum rate of increases predicted for human beings in the absence of mortality (r_m): 0.0281–0.0296, which agrees well with the cohort-based prediction [77] of r_m for humans = 0.03. Extending the facilitation relationship back to N_t (x) = 0 (intercept) gives $r_m = -0.001–0.001$ (median = 0.0003), the upper limit of which is close to the predicted rate of hunter-gatherer population growth derived from cohort-based models ($r_m = 0.003$) [77]. Red (Ricker) and green (Gompertz) shading around logistic fits indicate 95% confidence intervals.

correction for autocorrelation returning a slope of $\beta = -0.0025$—-0.0022 (i.e. nearly identical to the non-autocorrelation corrected confidence interval). Likewise, the 95% confidence intervals of the 10 000 slopes derived from the resampling approach assuming decreasing uncertainty in the population estimates were: 0.0083–0.0140 for the facilitation phase (i.e. positive slope), −0.0173–0.0394 for the transition phase (no relationship because the range includes slope = 0), and −0.0026—−0.0020 for the negative phase (i.e. negative slope). The general trends are therefore robust even with considerable but realistic uncertainty in the annual N_t.

The negative phase beginning in 1962 predates by 8 years the onset in 1970 where global consumption (ecological footprint) exceeded the Earth's biocapacity [29]. In 1970, the Earth transitioned to a global biocapacity deficit (required Earths >1; figure 2(a)) and has remained so since, likely driven by the rapid fossil fuel-enabled expansion of economic activities that became a global phenomenon following World War II. The phase shift did not arise from an abrupt shift in age structure—indeed, we found a decoupling between r and mean age, and r and proportion of 'young' (<15 years old) in the global population between 1950 and 1986 (figure S8).

3.2. Carrying capacity

Based on the Ricker logistic model, we predicted the population size at $r = 0$ (defined as the Ricker carrying capacity K_R) to occur at 11.66–12.40 billion people (figure 2(b)). Assuming no deviation from the expected relationship, we calculate that this would occur between 2067 and 2076 (figure 2(b)). The Newey–West autocorrelation-corrected estimate of K_R was 11.44–12.69 billion (i.e. slightly extending the confidence interval). The resampling approach described in the previous section where we added 1% uncertainty to the United Nations population estimates for the negative phase calculated a maximum population size from the Ricker logistic $K_\mathrm{R} = -\hat{\alpha}/\hat{\beta}$, where $\hat{\alpha}$ and $\hat{\beta}$ are the intercept and slope of the $r \sim N_t$ relationship [Ricker], respectively) of 11.59–13.36 billion, thereby agreeing with our deterministic (non-stochastic) prediction of 11.66–12.40 billion above.

Extending the Ricker logistic model to the intercept (where $N_t = 0$) to calculate the theoretical maximum rate of increase (r_m) gives 0.028–0.029, which agrees well with theoretical predictions of maximum population growth calculated for humans ($r = 0.03$) in the absence of mortality [77]. Likewise, we extended the facilitation relationship back to $N_t = 0$ to calculate $r_\mathrm{m} = -0.001$–0.001 (median $= 0.0003$), which also agrees with the realized r_m derived from cohort-based models for non-agropastoralist humans [77].

We estimated facilitation carrying capacity K_f by taking the maximum r during the 1800–1949 facilitation period ($r = 0.011$ from 1929–1930; figure 2(a)) to calculate a global population of approximately 2.47 billion (figure 2(a)). Of course, a truly 'sustainable' population with high average well-being would to some extent depend on many other characteristics beyond demography (e.g. structure, economics, social conditions). However, the general assumption that older, slower-growing populations are less-productive and have lower socio-economic performance than younger, faster-growing populations is not supported by data [78]. Additionally, our estimate of K_f is remarkably close to the global $K = 3.3$ billion previously estimated to allow all people to live in comfort economically [36]. From the perspective of a sustainable ecological footprint, we also calculated a K of 2.35 billion, assuming a consumption rate of 0.5 Earths to avoid overconsumption (compared to the 1.7 Earths consumed today) and current human population of 8 billion. Taking 1.7 (currently used) Earths ÷ 0.5 (target Earths) estimates that the global human population is 3.4 times too large, and that $K = 8$ billion ÷ 3.4 = 2.35 billion would be 'sustainable' at today's average material standard of living and current consumption distribution [29]. Incidentally, we show that the global population growth rate fell below $r = 0.011$ in 2018 and continues to decline since (figure 2(a)).

3.3. Regional differences

The strongest rate of decline of r with increasing N during the negative phase occurred in Oceania (signal dominated by Australia and New Zealand), then eastern and south-eastern Asia (figure 3(a)), followed by Europe/North America, and Latin America/Caribbean (figures 3(b), (c) and 4). The latter three regions also began their negative phase in the late 1950s or early 1960s (figures 3(a)–(c)) following the global trend (figure 2(a)). However, the remaining regions' negative phase began later (after 1975; figure 3), with Sub-Saharan Africa being the last region to begin a negative phase in 2010 (figure 3(g); excluding Oceania with Australia and New Zealand). 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_R given the shortest-available time series during the negative phase (figures 3(g) and 4). However, even the African countries with the highest fertilities globally still demonstrate signs of a shift to a negative phase over the last few decades (supplementary material appendix IV figure S9). Regional differences in the rate of decline in r with N during the negative phase suggest that (*i*) the rate of decline in population growth is faster in regions with lower mean fertility, (*ii*) wealthier regions (measured by GDP) have a faster decline in population growth, (*iii*) the earlier the onset of the negative phase, the faster the rate of decline in population growth, and (*iv*) there is possibly a faster decline in fertility from immediately before *versus* immediately after the transition to the decline phase in regions with the fastest decline in population growth (supplementary material appendix IV figure S10).

Extending the Ricker fits to $r = 0$ for each region's negative phase calculates K_R for each: 3.22–5.18 billion for Sub-Saharan Africa, 2.70–2.96 billion for central/southern Asia, 2.32–2.92 billion for eastern/south-eastern Asia, 0.98–1.46 billion for Europe/North America, 0.90–1.42 billion for

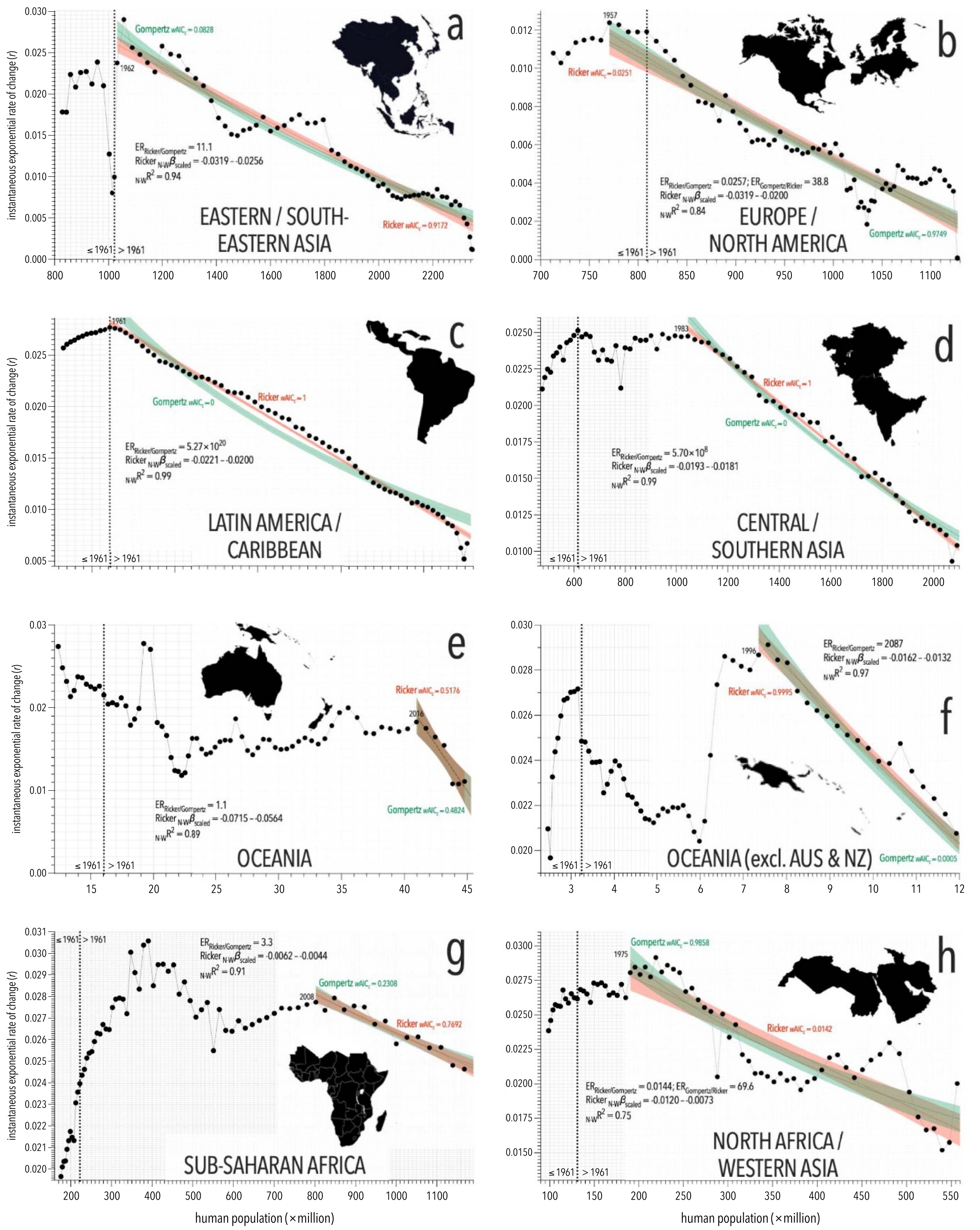

Figure 3. Relationship between the instantaneous (annual) exponential rate of change ($r = \log_e(N_{t+1}/N_t)$ and population size (N) (Ricker logistic) at year t from 1950 to 2023 for seven major global regions, sorted by descending magnitude of slope (rate of decline of r with increasing N; see also figure 4). Also shown are the Gompertz logistic relationships, and the Akaike's information criterion weights ($w\text{AIC}_c$) for each model mostly indicate dominant support for the Ricker model (or nearly identical dynamics from the Gompertz when that model's $w\text{AIC}_c$ is higher). N for each region are first scaled so that slopes are comparable (figure 4). (a) Eastern and south-eastern Asia, (b) Europe and North America, (c) Latin America and Caribbean, (d) central and southern Asia, (e) Oceania, (f) northern Africa and western Asia, (g) Sub-Saharan Africa. Vertical dotted line in each panel indicates the onset of the period of the negative phase (>1961) from the global data (figure 2). The year when the negative phase began in each region shown in each panel. Red (Ricker) and green (Gompertz) shading around logistic fits indicate 95% confidence intervals.

North Africa/Western Asia, 0.78–0.84 billion for Latin America/Caribbean, and 0.02–0.11 billion for Oceania (supplementary material appendix IV, Fig. S11). Summing these ranges gives 10.92–14.89 billion, which is a median of only 7.3% higher than the K_R we calculated from the global data combined (11.66–12.40 billion; figure 2(b)). Although we identified at least one period of facilitation in all regions as well (figure 3), the regional data only go back to 1950 and cannot be used reliably to infer the

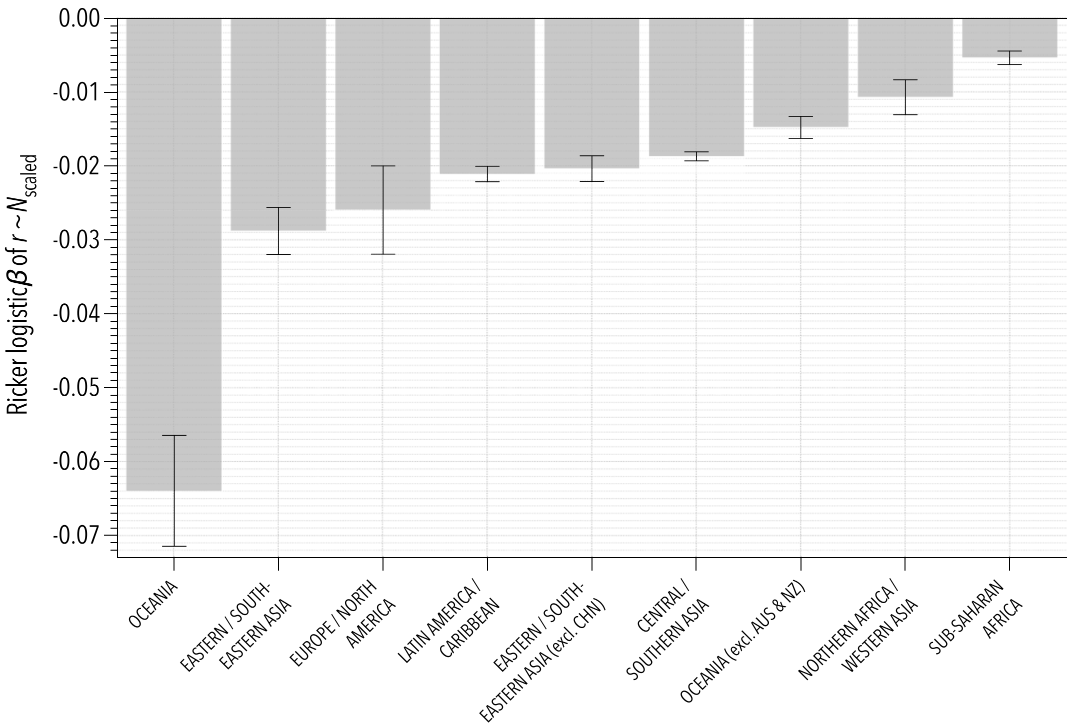

Figure 4. Resampled (10 000 iterations) of the Ricker logistic slope β, where more negative values indicate increasing rate of decline in the instantaneous exponential rate of annual growth ($r = \log_e(N_{t+1}/N_t)$ relative to population size (N, scaled, but not centered, using the *scale* function in R to ensure $\hat{\beta}$ are on the same scale) at time t per major global region from 1950–2023. Error bars indicate 95% confidence intervals. Regions ordered from most negative β to least negative β. See also figure 3.

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 ($R^2 = 0.92$) calculated rate of decline of r with increasing N (slope = -0.0346) compared to any other region (supplementary material appendix IV, figure S12(c)).

3.4. Correspondence to projections

Our calculated estimate of K_R from the Ricker logistic model applied to the negative phase (figure 2(b)) demonstrates the best correspondence to the United Nations *High* [1] and IIASA-JRC *Stalled* scenarios [54, 55], but with plateauing occurring as in the United Nations *Medium* and *Probabilistic*, and the IIASA-JRC *Reference* scenarios (figure 5). This correspondence supports the higher predictions of population growth under the United Nations *High* and IIASA-JRC *Stalled* scenarios, but with stabilization and possibly decline starting from around 2070 (figure 5).

3.5. Indices of global change

As we hypothesized, we found that the global temperature anomaly was most strongly and positively correlated with the global human population size from 1962 onwards ($_{\text{N–W}}R^2$ = 0.911–0.928; figure 6(b)), even after accounting for temporal autocorrelation. Although we also calculated a positive correlation between temperature anomaly and human population size during the facilitation phase, it is weaker ($_{\text{N–W}}R^2$ = 0.197–0.353; figure 6(b)). Human population size was also a stronger predictor of temperature anomaly, global ecological footprint, and total annual CO_2-e emissions than was per-capita energy consumption (supplementary material appendix III), although we acknowledge that this simple model ignores the complex contribution of technological innovation [79] inherent in any relationship between global change and population size and consumption [80].

4. Discussion

Our predictions of global sustainable carrying capacity and maximum population size are the first to be based on human population time series alone, and the simplicity of phenomenological models [20]. A meta-analysis by van den Bergh and Rietveld [23] examined 51 studies that produced 94 estimates of a limit to the global human population. Their median meta-prediction from these 51 studies was 7.7 billion people, but ranged from 650 million assuming a low-technology future where water availability is the main limiting factor, to 288 billion under the assumption of the 'best' future technology for all countries (with most estimates well above currently projected future global population sizes). The

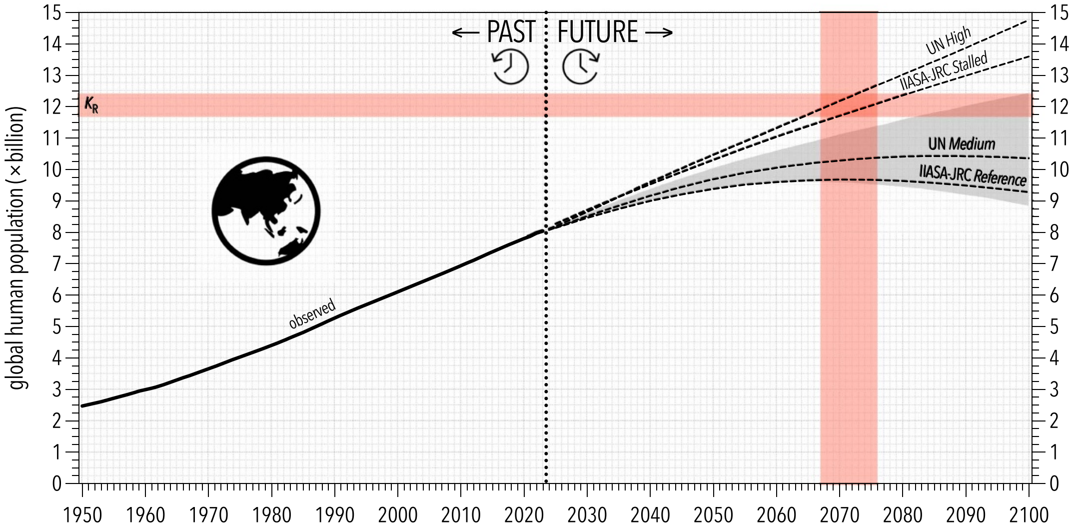

Figure 5. Past trajectory and future projections of the global human population from the most-plausible [31] models of the United Nations (UN) and IIASA-JRC. Dotted black lines are the *Medium* and *High* scenarios from the UN [1], and the *Reference* and *Stalled* scenarios from the IIASA-JRC [54, 55]; gray-shaded area is the 95% confidence interval for the UN *Probabilistic* Population Projections [1]. Red shading indicates the maximum human carrying capacity derived from the Ricker model ($K_R = 11.66$–12.40) and timing (2067–2076) derived from figure 2(b).

uncertainty stems mainly from the many different assumptions and dimensions considered in the projections, a problem we avoided by basing our estimates of maximum and sustainable carrying capacity on the population data alone. Others have investigated the multivariate relationships of several human demographic rates and socio-economic factors relative to human density across different spatial scales [2, 81–83]. For example, Lutz *et al* [2] found strong relationships between country-level total fertility rate and population density (measured per area of arable land), but only a weak relationship between r and population density. However, no previous study has investigated the evidence for relationships between r and N at the global or regional scales as we did here.

The mechanisms driving the phenomenon of a decline in r within increasing global human population size are necessarily complex, and likely include both direct and indirect pathways leading to reduced population growth. Population growth is an ensemble property emerging primarily from two main component demographic rates—fertility and survival [20]. In modern human societies, fertility has the greatest effect on population growth [2], and indeed declined during the negative phase globally and regionally (supplementary material appendix IV figure S13). In contrast, survival (measured as the life expectancy at birth) increased throughout the negative $r \sim N$ phase, despite population growth simultaneously declining (supplementary material appendix IV figure S14). However, although the onsets of the fertility declines were contemporaneous with the beginning of the negative $r \sim N$ phase globally (figure S14(a)) and in eastern/south-eastern Asia, Europe/North America, and Latin America/Caribbean (figures S14(b)–(d)), they began earlier than the onset of the negative phase in central/southern Asia, Oceania, north Africa/western Asia, and Sub-Saharan Africa (supplementary material figures S12(e)–(h)). The fact that the lowest-income regions of the world began their descent into the negative $r \sim N$ phase later than in higher-income regions (where development started earlier) also supports the notion that the intensity of development via the exploitation of fossil fuels was the main driver of the transition from facilitation.

The extent to which human population growth varies in response to (*i*) environmental constraints such as access to sufficient land, and the efficiency with which we can extract and consume fresh water, food, energy, and other material resources [23], (*ii*) decreasing fertility from chemical exposure [84], and (*iii*) people choosing to reduce fertility (e.g. following the principles outlined in the 'demographic transition' paradigm) [85] are context-specific. Indeed, any negative feedback is not required to act through direct biological mechanisms alone, because even perceptions of population impacts [53] (e.g. crowding, competition for resources, conflict) can be psychological determinants of human choices regarding fertility [2, 25, 36], empowerment, and reduced child mortality [86]. Enhanced by the exploitation of fossil fuels (e.g. household automation technologies), these components have ironically also played a strong role in fertility reductions globally.

The abrupt switch from a positive to a negative phase in the calculated relationship between r and N demonstrates that human ingenuity, technology, energy production, and social structure have

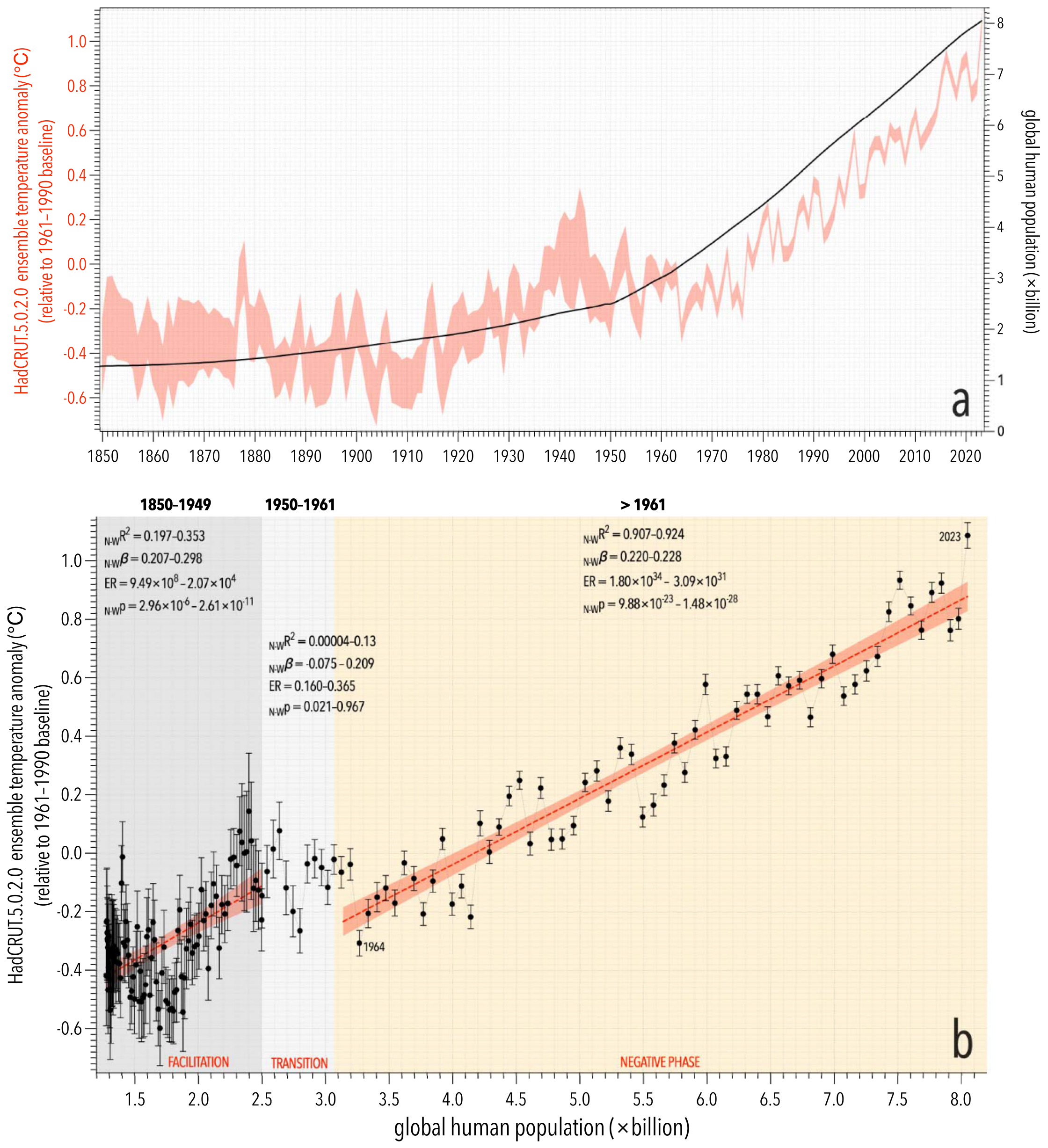

Figure 6. (a) Global human population size (black line; right y axis) with the 95% confidence interval of the global temperature anomaly (°C) derived from the HadCRUT.5.0.2.0 ensemble model [56] compared to the 1961–1990 baseline superimposed (red; left y axis). (b) Relationship between global human population size and temperature anomaly for the three main phases of human demography from 1850 to the present: *i*. Facilitation (1850–1949; dark gray background shading), *ii*. Transition (1950–1961; light gray background shading), and *iii*. The negative phase (1962–2023; peach background shading). Shown for each phase are the 95% confidence intervals for the linear-model evidence ratios (ER), and the Newey–West heteroscedasticity- and autocorrelation-corrected goodness of fits ($_{\mathrm{N-W}}R^2$), slopes ($_{\mathrm{N-W}}\beta$), and probabilities of Type I error ($_{\mathrm{N-W}}\mathrm{p}$). Red shading indicates 95% confidence interval of the linear fits in phases *i* and *iii*.

not led to higher human population growth since the 1940s. While estimates of human carrying capacity derived from logistic models are straightforward and elegant, they cannot necessarily predict the future. Our estimates assume that the form of the Ricker logistic model will remain constant until $r = 0$, but global phenomena such as unmitigated climate change and environmental collapse [87–89] could, because of cumulative effects, decouple the calculated linear relationship between r and N sooner. Our approach also assumes that population size is equivalent to *density* (individuals per unit area), the latter of which has more direct mechanistic influences on human demography such as child morbidity and mortality [90], infectious disease [91], and total fertility rate [2] than population size *per se*. Nonetheless, the ensemble signal strength of the negative phase is rather insensitive to variation in carrying capacity itself, although it tends to underestimate component effects (i.e. how sensitive demographic rates are to changes in population size) when abundance is trending strongly over time [20]. Given that the global human population has been increasing consistently on average for thousands of years, and is still at one of its highest rates of increase, the rate of the decline in r with increasing N we observed in the global data is likely under- rather than over-estimated. This suggests that the negative phase will continue unabated for several more decades at least.

Regardless, it is clear that Earth cannot sustain the future human population, or even today's, without a major overhaul of socio-cultural practices for using land, water, energy, biodiversity, and other resources [22]. As such, some form of societal downscaling [sensu 22] appears inevitable, whether achieved actively or in response to continued declines in population growth [27]. Instead of focusing on a 'maximum' carrying capacity, the number of humans that can be safely imposed on the environment is a function of both population size and per-capita consumption [26, 80], both of which are continuing to rise [53]. As such, any form of future development under the umbrella of 'sustainability' must meet the needs and aspirations of present societies while simultaneously ensuring that future generations can meet their own [37]. This cannot be achieved in the pursuit of a maximum population size, no matter how well-defined, especially considering that smaller populations beget more individual and environmental benefits [53]. Today's economies predicated on uninterrupted growth apparently [92] do not recognize the regenerative constraints of sustained population expansion, because fossil fuels artificially make up the difference [93]. Nor do economies anticipate the looming reductions in regenerative capacity as climate disruptions intensify [92]. The tragedy is that human endeavor has short-circuited the ultimately inevitable corrective feedback loops carrying capacity imposes, without replacing them with humane and environmentally friendly corrective feedbacks.

Acknowledgment

The Kids Research Institute Australia and Population Matters supported various aspects of the project.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10951676 [94].

Author contributions

Corey J A Bradshaw 0000-0002-5328-7741
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Resources (lead), Software (lead), Validation (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Melinda A Judge
Writing – review & editing (supporting)

Daniel T Blumstein
Writing – review & editing (supporting)

Paul R Ehrlich
Writing – review & editing (supporting)

Aisha N Z Dasgupta
Writing – review & editing (supporting)

Mathis Wackernagel
Writing – review & editing (supporting)

Lewis J Z Weeda 0000-0002-8920-9104
Writing – review & editing (supporting)

Peter N Le Souëf
Writing – review & editing (supporting)

References

[1] United Nations Department of Economic and Social Affairs Population Division 2022 World population prospects 2022: summary of results (available at: un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf)

[2] Lutz W, Qiang R, Sibly R M, Hone J and Clutton–Brock T H 2002 Determinants of human population growth *Phil. Trans. R. Soc. B* **357** 1197

[3] Kohler H-P 1997 Learning in social networks and contraceptive choice *Demography* **34** 369

[4] Rentería E, Souto G, Mejía-guevara I and Patxot C 2016 The effect of education on the demographic dividend *Popul. Dev. Rev.* **42** 651

[5] Boling P 2008 Demography, culture, and policy: understanding Japan's low fertility *Popul. Dev. Rev.* **34** 307

[6] Fogarty L, Creanza N and Feldman M W 2013 The role of cultural transmission in human demographic change: an age-structured model *Theor. Popul. Biol.* **88** 68

[7] Moehling C M and Thomasson M A 2014 Saving babies: the impact of public education programs on infant mortality *Demography* **51** 367

[8] Mosley W H and Becker S 1991 Demographic models for child survival and implications for health intervention programmes *Health Policy Plann.* **6** 218

[9] Kramer K L, Hackman J, Schacht R and Davis H E 2021 Effects of family planning on fertility behaviour across the demographic transition *Sci. Rep.* **11** 8835

[10] Smock P J and Schwartz C R 2020 The demography of families: a review of patterns and change *J. Marr. Fam.* **82** 9–34

[11] Bradshaw C J A and Brook B W 2016 Implications of Australia's population policy for future greenhouse-gas emissions targets *Asia Pac. Policy Stud.* **3** 249

[12] Kugler T, Kang K K, Kugler J, Arbetman-Rabinowitz M and Thomas J 2013 Demographic and economic consequences of conflict *Int. Stud. Q.* **57** 1–12

[13] Siuda F and Sunde U 2021 Disease and demographic development: the legacy of the plague *J. Econ. Growth* **26** 1–30

[14] Demetrius L 1989 The demographic evolution of human populations: the role of selection and environmental factors *Demography* **26** 353

[15] Hunter L M and Simon D H 2021 Environmental demography *Handbook of Environmental Sociology* ed B Schaefer Caniglia, A Jorgenson, S A Malin, L Peek, D N Pellow and X Huang (Springer) p 405

[16] Pebley A R 1998 Demography and the environment *Demography* **35** 377

[17] Berryman A A and Turchin P 2001 Identifying the density-dependent structure underlying ecological time series *Oikos* **92** 265
[18] Berryman A A 1999 *Principles of Population Dynamics and Their Application* (Stanley Thorners Ltd)
[19] Pulliam H R and Haddad N M 1994 Human population growth and the carrying capacity concept *Bull. Ecol. Soc. Am.* **75** 141
[20] Bradshaw C J A and Herrando-pérez S 2023 Logistic-growth models measuring density feedback are sensitive to population declines, but not fluctuating carrying capacity *Ecol. Evol.* **13** e10010
[21] Herrando-Pérez S, Delean S, Brook B W and Bradshaw C J A 2012 Density dependence: an ecological Tower of Babel *Oecologia* **170** 585
[22] Ellis E C 2023 The anthropocene condition: evolving through social–ecological transformations *Phil. Trans. R. Soc. B* **379** 20220255
[23] van den Bergh J C J M and Rietveld P 2004 Reconsidering the limits to world population: meta-analysis and meta-prediction *BioScience* **54** 195
[24] Barrett G W and Odum E P 2000 The twenty-first century: the world at carrying capacity *BioScience* **50** 363
[25] Cohen J E 1997 Population, economics, environment and culture: an introduction to human carrying capacity *J. Appl. Ecol.* **34** 1325
[26] Rees W E 1996 Revisiting carrying capacity: area-based indicators of sustainability *Popul. Environ.* **17** 195
[27] Bradshaw C J A *et al* 2021 Underestimating the challenges of avoiding a ghastly future *Front. Conserv. Sci.* **1** 615419
[28] Ceballos G and Ehrlich P R 2023 Mutilation of the tree of life via mass extinction of animal genera *Proc. Natl Acad. Sci. USA* **120** e2306987120
[29] Wackernagel M, Hanscom L, Jayasinghe P, Lin D, Murthy A, Neill E and Raven P H 2021 The importance of resource security for poverty eradication *Nat. Sustain.* **4** 731
[30] Ravallion M 2020 On measuring global poverty *Annu. Rev. Econ.* **12** 167
[31] Judge M A, Saraswati C, Weeda L Z, Bassat Q, Prata N, Le Souëf P N and Bradshaw C A 2024 Long-term benefits of curbing human population growth *SSRN* (https://doi.org/10.2139/ssrn.4795464)
[32] Chong B *et al* 2023 Trends and predictions of malnutrition and obesity in 204 countries and territories: an analysis of the global burden of disease study 2019 *eClinicalMedicine* **57** 101850
[33] FAO 2022 The state of food security and nutrition in the world 2022 (available at: fao.org/documents/card/en/c/cc0639en)
[34] Ehrlich P R, Kareiva P M and Daily G C 2012 Securing natural capital and expanding equity to rescale civilization *Nature* **486** 68
[35] Bauch C T 2008 Wealth as a source of density dependence in human population growth *Oikos* **117** 1824
[36] Dasgupta P, Dasgupta A and Barrett S 2023 Population, ecological footprint and the sustainable development goals *Environ. Resour. Econ.* **84** 659
[37] Daily G C and Ehrlich P R 1992 Population, sustainability, and Earth's carrying capacity *BioScience* **42** 761
[38] Biraben J N 1980 An essay concerning mankind's demographic evolution *J. Hum. Evol.* **9** 655
[39] Durand J D 1977 Historical estimates of world population: an evaluation *Popul. Dev. Rev.* **3** 253
[40] Gapminder 2002 Gapminder v7—Systema Globalis 2022 (available at: github.com/open-numbers/ddf–gapminder–systema_globalis)
[41] Haub C 1995 How many people have ever lived on Earth? *Popul. Today* **23** 4–5
[42] Hyde 2017 Hyde 3.2 (available at: hyde-portal.geo.uu.nl)
[43] McEvedy C and Jones R 1978 *Atlas of World Population History* (Penguin Books, Harmondsworth)
[44] Ritchie H, Rodés-Guirao L, Mathieu E, Gerber M, Ortiz-Ospina E, Hasell J and Roser M 2024 Our world in data (Population Growth) (available at: ourworldindata.org/population-growth)
[45] Thomlinson R 1978 *Demographic Problems: Controversy Over Population Control* (Dickenson Publishing Company)
[46] United Nations Department of Economic and Social Affairs 1973 The determinants and consequences of population trends: new summary of findings of interaction of demographic, economic and social factors. United Nations, New York, USA
[47] Ricker W E 1958 *Handbook of Computations for Biological Statistics of Fish Populations* (Fisheries Research Board of Canada)
[48] Nelder J A 1961 The fitting of a generalization of the logistic curve *Biometrics* **17** 89
[49] Ritchie H 2023 The UN has made population projections for more than 50 years—how accurate have they been? (available at: ourworldindata.org/population-projections)
[50] Keilman N 2001 Data quality and accuracy of United Nations population projections, 1950–95 *Popul. Stud.* **52** 149
[51] Clark F, Brook B W, Delean S, Akçakaya H R and Bradshaw C J A 2010 The theta-logistic is unreliable for modelling most census data *Methods Ecol. Evol.* **1** 253
[52] Stephens P A, Sutherland W J and Freckleton R P 1999 What is the Allee effect? *Oikos* **87** 185
[53] Saraswati C M, Judge M A, Weeda L J Z, Bassat Q, Prata N, Le Souëf P N and Bradshaw C J A 2024 Net benefit of smaller human populations to environmental integrity and individual health and well-being *Front. Pub. Health* **12** 1339933
[54] Lutz W, Goujon A, Samir K C, Stonawski M and Stilianakis N 2018 Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries Report No. 9279780239
[55] Wittgenstein Center for Demography and Global Human Capital 2018 Wittgenstein centre human capital data explorer version 2.0 (available at: dataexplorer.wittgensteincentre.org/wcde-v2)
[56] Morice C P, Kennedy J J, Rayner N A, Winn J P, Hogan E, Killick R E, Dunn R J H, Osborn T J, Jones P D and Simpson I R 2021 An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set *J. Geophys. Res.* **126** e2019JD032361
[57] Johnson N P A S and Mueller J 2002 Updating the accounts: global mortality of the 1918–1920 "Spanish" influenza pandemic *Bull. Hist. Med.* **76** 105
[58] The Polynational War Memorial 2023 The polynational war memorial (available at: war-memorial.net)
[59] Wemheuer F and Dikötter F 2011 Sites of horror: Mao's great famine *China J.* **66** 155
[60] Esdaile C 2007 *Napoleon's Wars: An International History, 1803–1815* (Allen Lane)
[61] Ross D 2002 *Ireland: History of a Nation* (Geddes & Grosset) pp 384
[62] Platt S R 2012 *Autumn in the Heavenly Kingdom. China, the West, and the Epic Story of the Taiping Civil War* (Alfred A. Knopf)
[63] Lu W 2003 The loss of population in Shaanxi during the reign of Tongzhi and Guangxu (Historical Geography) p 19
[64] Digby W 1901 *'Prosperous' British India* (T. Fisher Unwin)
[65] Li L M 2007 *Fighting Famine in North China. State, Market, and Environmental Decline, 1690s-1990s* (Stanford University Press)
[66] Davis M 2000 *Late Victorian Holocausts: El Niño Famines and the Making of the Third World* (Verso)
[67] Majd M G 2013 *The Great Famine & Genocide in Iran, 1917–1919* 2nd edn (University Press of America)
[68] Patenaude B M 2002 *The Big Show in Bololand. The American Relief Expedition to Soviet Russia in the Famine of 1921* (Stanford University Press)
[69] Wolowyna O 2021 A demographic framework for the 1932–1934 famine in the Soviet Union *J. Genocid. Res.* **23** 501
[70] Rummel R J 1991 *China's Bloody Century: Genocide and Mass Murder since 1900* (Routledge)

[71] Nwaubani A T 2020 Remembering Nigeria's Biafra war that many prefer to forget, London, United Kingdom (available at: bbc.com/news/world-africa-51094093)

[72] Stevenson J A 2014 Capitol gains: how foreign military intervention and the elite quest for international recognition cause mass killing in new states *PhD Thesis* Department of Political Science, University of Chicago (available at: proquest.com/openview/12b3ce5a0745f62d3448a5fb0d06f81f/1)

[73] Heuveline P 2001 *The Demographic Analysis of Mortality in Cambodia in Forced Migration and Mortality* ed H E Reed and C B Keely (National Academy Press)

[74] Lacina B and Gleditsch N P 2005 Monitoring trends in global combat: a new dataset of battle deaths *Eur. J. Popul.* **21** 145

[75] McGreal C 2008 *Congo Conflict Causes 45,000 Deaths a Month: Study* (The Guardian) (available at: theguardian.com/world/2008/jan/22/congo.chrismcgreal)

[76] Msemburi W, Karlinsky A, Knutson V, Aleshin-Guendel S, Chatterji S and Wakefield J 2023 The WHO estimates of excess mortality associated with the COVID-19 pandemic *Nature* **613** 130

[77] Bradshaw C J A *et al* 2021 Stochastic models support rapid peopling of Late Pleistocene Sahul *Nat. Commun.* **12** 2440

[78] Bradshaw Corey J A and McDermott S M 2025 No evidence ageing or declining populations compromise socioeconomic performance of countries (arXiv:2508.16872)

[79] York R and McGee J A 2016 Understanding the Jevons paradox *Environ. Sociol.* **2** 77

[80] Ehrlich P R and Holdren J 1971 Impact of population growth *Science* **171** 1212

[81] Adelman I 1963 An econometric analysis of population growth *Am. Econ. Rev.* **53** 314

[82] Heer D M 1966 Economic development and fertility *Demography* **3** 423

[83] Janowitz B S 1971 An empirical study of the effects of socioeconomic development on fertility rates *Demography* **8** 319

[84] Skakkebæk N E *et al* 2022 Environmental factors in declining human fertility *Nat. Rev. Endocrinol.* **18** 139

[85] Kirk D 1996 Demographic transition theory *Popul. Stud.* **50** 361

[86] Bradshaw C J A, Perry C, Judge M A, Saraswati C M, Heyworth J, Le Souëf P N and Amo-Adjei J 2023 Lower infant mortality, lower household size, and more access to contraception reduce fertility in low- and middle-income nations *PLoS One* **18** e0280260

[87] Dasgupta P S and Ehrlich P R 2013 Pervasive externalities at the population, consumption, and environment nexus *Science* **340** 324

[88] Ehrlich P R and Ehrlich A H 2013 Can a collapse of global civilization be avoided? *Proc. R. Soc. B* **280** 20122845

[89] Richardson K *et al* 2023 Earth beyond six of nine planetary boundaries *Sci. Adv.* **9** eadh2458

[90] Bradshaw C J A, Otto S P, Annamalay A A, Heft-Neal S, Wagner Z and Le Souëf P N 2019 Testing the socioeconomic and environmental determinants of better child-health outcomes in Africa: a cross-sectional study among nations *BMJ Open.* **9** e029968

[91] Fatima S H, Judge M A, Le Souëf P N and Bradshaw C J A 2025 Impact of climate change on diarrhoea risk in low- and middle-income countries *Environ. Res.* **285** 122412

[92] Murphy T W 2022 Limits to economic growth *Nat. Phys.* **18** 844

[93] Brown J H *et al* 2011 Energetic limits to economic growth *BioScience* **61** 19–26

[94] Available at: https://doi.org/10.5281/zenodo.10951676