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REPLY

Reply to comment on '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], Aisha N Z Dasgupta[7], Mathis Wackernagel[8], Lewis J Z Weeda[9] and Peter N Le Souëf[9]

[1] Global Ecology |*Partuyarta Ngadluku Wardli Kuu*, College of Science and Engineering, Flinders University, Adelaide, South Australia, 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, CA, United States of America
[6] Institute of the Environment and Sustainability, University of California, Los Angeles, CA, United States of America
[7] Judge Business School, University of Cambridge, Cambridge, United Kingdom
[8] Global Footprint Network, Oakland, CA, United States of America
[9] School of Medicine, University of Western Australia, Nedlands, Western Australia, Australia
[*] Author to whom any correspondence should be addressed.

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

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Abstract

Haubrock (2026 *Environ. Res. Lett.*) criticizes Bradshaw *et al* (2026 *Environ. Res. Lett.* **21** 064023), but relies on strawman arguments, misrepresents demographic transition theory, and downplays environmental contingencies. We respond point-by-point to seven claims concerning (i) the interpretation of the post-1960 decline in r as evidence of exceeded carrying capacity; (ii) use of phenomenological logistic models in a non-stationary human system; (iii) global N as a proxy for density feedback; (iv) shared-trend confounding in environmental correlations; (v) normative elements of 'sustainable carrying capacity'; (vi) alleged population-centred framing; and (vii) whether the title overstates the evidence (Haubrock 2026 *Environ. Res. Lett.*). We show that demographic transition theory is primarily descriptive and does not require a declining growth rate: whether growth slows depends on the timing and magnitude of fertility–mortality gaps, which vary historically and culturally. Indeed, fertility transitions can occur at modest incomes under strong institutional and ideational influences. Haubrock's argument here rests on an uncritical acceptance of demographic transition theory, false dichotomies between socio-economic and ecological mechanisms, and an overly restrictive interpretation of what phenomenological models infer from abundance time series. Our central result remains an abrupt, persistent shift from facilitation to strong negative r–N feedback beginning ~1961–1962, consistent with emergent ensemble density feedback mediated by socio-economic and environmental constraints. We clarify that subnational density inference is infeasible due to inadequate fine-scale population data in many countries, that our environmental correlations are corroborative rather than causal and should be interpreted with appropriate time-series cautions, and that population drivers are underrepresented in the mainstream institutions/technology-centred literature despite strong evidence of population effects identified in IPAT/STIRPAT analyses.

1. Introduction

Haubrock [1] attempts a critique of Bradshaw *et al* [2], but instead relies on strawman arguments, misinterprets demographic theory, and underplays the importance of environmental contingencies. Haubrock's comment [1] lists seven points of critique: (i) interpretation of the post-1960 decline in r as evidence of exceeded carrying capacity; (ii) appropriateness of phenomenological logistic models for a non-stationary human system; (iii) use of global population size as a proxy for density feedback; (iv) shared-trend confounding in environmental correlations; (v) normative elements in 'sustainable carrying capacity'; (vi) alleged population-centred framing; and (vii) whether the title overstates the evidence. Below we respond point-by-point and delineate what our analyses do—and do not—claim.

2. The $r \sim N$ regime shift cannot be explained away by demographic transition theory

Haubrock [1] argues that the observed post-1960 decline in the instantaneous exponential growth rate (r) as population size (N) increases is consistent with 'demographic transition theory' [3] and thus not diagnostic of ecological constraints. This argument is misplaced for several reasons. First, demographic transition theory is a descriptive, and not an explanatory, generalisation (societies shift from high fertility/high mortality to low fertility/low mortality). The theory does not specify a single causal driver or an invariant sequence for how those declines must unfold. Consequently, whether population growth declines depends on the timing and magnitude of the fertility-mortality gap. Lee [4] described the 'classic' case where mortality falls first and fertility later, which makes population growth initially accelerate then slow; however, he explicitly highlighted exceptions where fertility declines first, implying that demographic transition theory does not require a declining growth rate if fertility and mortality fall synchronously.

Early formulations of demographic transition theory emphasised economic development, but subsequent research has demonstrated that fertility decline can occur at low incomes and that cultural, institutional, and political factors are often decisive [3, 5]. The theory also underplays ideational norms, values, and preferences by treating fertility decline as a rational response to economic change. In fact, diffusion of ideas about family size, contraception, gender equity, and modernity can drive fertility transitions independently of material conditions [6–8]. The Indian state of Kerala is a well-documented example where below-replacement fertility occurred at modest incomes. By the 1990s, Kerala had reached below-replacement fertility (total fertility rate ~1.8 in 1991), and this transition is widely attributed to institutional and social determinants such as widespread education, provision of public-health services, and emplacing processes to empower women rather than a high per-capita gross domestic product [4, 9]. In contrast, high-income Gulf states had much higher fertility over comparable decades (from 1980 to 2000, mean total fertility rate ~5.78 in Saudi Arabia and ~4.34 in the United Arab Emirates) despite high and rising per-capita gross domestic product [10].

This lack of both causal and phenomenological requirements notwithstanding, Haubrock's [1] argument also rests entirely on accepting 'demographic transition theory' as an immutable demographic law. However, the theory itself is flawed for many reasons [4], mainly because it was derived inductively from Western European experience and then generalised falsely as a universal model. Fertility and mortality declines in Europe unfolded under specific historical conditions—industrialisation, colonial resource flows, and early welfare institutions—that do not necessarily apply elsewhere. Applying this theory as a catch-all treats European trajectories as normative rather than contingent on specific regional characteristics [3], and so instead Haubrock [1] himself is guilty of his normative accusation. Haubrock's argument is also a strawman because demographic transition theory is not a mechanistic alternative to ecological feedback; rather, it is one set of behavioural and institutional pathways through which environmental and economic conditions can influence demographic rates. As emphasised in modern treatments, transition dynamics are conditional on development pathways and incentives, and they coexist with multi-causal drivers including biological and environmental stressors [11, 12].

Our inference is not that 'r declines therefore carrying capacity is exceeded'. The important empirical result is a historically abrupt and persistent shift from a long facilitation phase (positive $r \sim N$) to a strong negative $r \sim N$ relationship beginning around 1961–1962, with high explanatory power during the negative phase and consistent expression across regions with expected heterogeneous timing [2]. Demographic transition theory's weaknesses aside, it does not predict a near-linear, monotonic dependence of r on global N across decades. The emergence of a coherent negative $r \sim N$ regime therefore remains an empirical fact requiring explanation.

Ecological theory distinguishes density feedback operating on vital rates ('component feedback') from density feedback detectable in abundance-derived growth rates ('ensemble feedback') [13–15]. In human populations, feedback can be mediated indirectly—via institutions, perceptions, costs of childrearing, conflict risk and health—without requiring immediate famine or elevated mortality [2, 16]. Additionally, evidence indicates that reproductive health trends in industrialised regions can be influenced by environmental exposures associated with fossil-fuel-based industrial metabolism, providing a biological channel that can reinforce behavioural transitions [12].

3. Phenomenological logistic models are appropriate

Haubrock [1] contends that applying a Ricker logistic model to humans is inappropriate because human populations are non-stationary. Phenomenological models are designed precisely for such settings: they estimate the net (ensemble) relationship between r and N without asserting a fixed mechanistic pathway (i.e. any potential decoupling of ensemble from component feedback due to non-stationarity here is irrelevant). This approach is standard in population ecology when the objective is to quantify the sign and strength of a density-feedback signal from abundance time series, recognising that mechanisms can be complex or changing [13, 14]. Accordingly, our $r \sim N$ fits are appropriately interpreted as an emergent summary of net feedback in the observed historical regime, and we explicitly caution that future technological or climatic shifts could decouple the relationship (and thus invalidate extrapolation), even though there has been no deviation from the negative $r \sim N$ relationship for >60 years [2].

4. Population size as a global state variable, heterogeneity, and aggregation

Haubrock [1] argues that total global N is a poor proxy for density and that aggregation masks heterogeneity. We explicitly acknowledge that N is not a mechanistic substitute for local density, and we treat it as a global-scale state variable appropriate to the Earth-system framing of the question [2]. More importantly, there is a dearth of robust population data at subnational scales for many countries (especially in sub-Saharan Africa) [17], because recent, reliable subnational population counts are often lacking, censuses can be outdated, inaccurate or omit areas [18], registration is incomplete, and fine-scale administrative boundaries linking counts spatially are limited [19]. Together, these data shortcomings prevent defensible subnational assessments of spatially heterogeneous density [18, 19]. Additionally, spatial heterogeneity and trade do not remove constraints in a globally integrated economy; they redistribute it. Because of global trade, most, if not all countries, are exposed to global resource dynamics, as experienced in the food shocks following the Russian invasion of Ukraine in February 2022 or the oil supply shocks after the Strait of Hormuz blockade beginning in February 2026. Area- and biocapacity-based analyses have been developed to capture precisely this displacement of demand across places and time, because local demand is no longer limited by local biocapacity [20].

Our regional analyses also directly counter the aggregation concern. Negative $r \sim N$ relationships emerge across United Nations regions, with earlier onset and steeper slopes in regions that industrialised earlier and have lower fertility, and later onset in high-fertility regions; summed regional carrying-capacity ranges are close to the global estimate [2]. This pattern is consistent with heterogeneous component processes contributing to a coherent global ensemble signal, not with ecological fallacy. Moreover, the interpretation of density feedback explicitly includes social mechanisms (e.g. cooperation, competition) and need not be confined to purely trophic limitation [3].

5. Environmental correlations, shared trends, and what we did (not) claim

Haubrock [1] correctly notes that regressions among co-trending, non-stationary series can generate spurious associations and that Newey–West corrections address autocorrelation but not unit-root non-stationarity. This is well-established in econometrics: regressions in integrated processes can yield misleading inference unless cointegration is considered [21, 22]. Two clarifications are essential. First, our principal demographic inference is not based on environmental correlations but on the $r \sim N$ regime shift itself, where r is constructed as a log ratio ($\log_e[N_{t+1}/N_t]$) that is typically closer to stationarity than level variables [21]. Second, we do not present bivariate environmental correlations as causal proof; we instead report them as corroborative concordance with the demographic regime shift and with independently calculated overshoot metrics [2, 23]. We welcome future work applying cointegration/error-correction approaches to long climatic and emissions time series, but this does not negate our descriptive phase-specific findings.

Furthermore, the extensive IPAT/STIRPAT (**I**mpact = **P**opulation × **A**ffluence × **T**echnology /**ST**ochastic **I**mpacts by **R**egression on **P**opulation, **A**ffluence and **T**echnology) literature—built specifically to separate population, affluence, and technology effects—has definitively established that population has a persistent, often near-proportional elasticity for CO_2 emissions and related impacts, even when allowing for nonlinearity and additional covariates [24, 25]. Indeed, reviews of national emissions drivers conclude that population and affluence clearly increase environmental stress and that evidence for systematic 'amelioration' at high affluence is equivocal [26–34], weak [35], or non-existent [36].

6. Sustainable carrying capacity: normativity, transparency, and appropriate interpretation of footprints

Haubrock [1] argues that our 'sustainable' carrying-capacity benchmark is normative, being tied to (*i*) the population size at maximum facilitative r and (*ii*) ecological-footprint scaling to a consumption target. We agree that 'sustainable' carrying capacity cannot be value-free: it depends on assumptions about minimum acceptable consumption, equity, and environmental risk or environmental quality (such as how to manage potential conflicts between human demand and biodiversity conservation), which has long been recognised in the carrying-capacity literature [23, 37]. But the idea of over-population is anything but normative; instead, the perception that human overpopulation is not a concern dominates the current *zeitgeist* [38–43]. However, our paper only distinguishes a maximum population size implied by $r \to 0$ in the observed negative regime from lower, sustainability-relevant benchmarks [2]; we do not promulgate a normative position.

Haubrock's [1] cited critique of the ecological-footprint metric [44] here is irrelevant because the footprint is intended as a minimum condition for sustainability, not a guarantee, and methodological improvement of the metric is ongoing [45, 46]. However, these limitations are immaterial here because our usage follows the conservative interpretation: the footprint-based computation is as a transparent scaling exercise conditional on an explicit target (here, that human demand <1 Earth), corroborated by the independent empirical benchmark derived from the facilitation phase [2]. Whether we use 0.5, 0.6, 0.7, … or any other value <1.0 Earths to provide a multiplier of excess humans causing a biocapacity deficit (e.g. 3.4×, 2.8×, 2.4×, … people above a long-term sustainable size) is inconsequential; but it *is* important that these resulting multipliers are ≫1 and that there is convergence of biocapacity deficit- [47], economic- [48], and demographic-based [2] estimates. Regardless, the biocapacity deficit-based estimate is calculated independently of the demographic-based one, and so our conclusions are unaffected by the choice of the target number of Earths consumed.

7. Framing, title, and scope of inference

Haubrock [1] suggests our framing 'privileges' population over institutions and technology and that the title overstates the evidence. Yet, the evidence is instead that human population considered as a plausible driver of variation in mainstream climate, energy, and environmental governance research is the forgotten child. Indeed, bibliometric evidence indicates a strong asymmetry—even in sustainability-modelling domains, technology-centred research is an order of magnitude more common than population-explicit causal frameworks (e.g. 13 869 'technology-variable' modelling records *versus* 1,369 STIRPAT records) [49], whereas mainstream climate-energy policy research alone numbers in the thousands of articles [50]. Therefore, non-population frameworks far exceed the population-driver literature captured in STIRPAT-focused syntheses. Our analysis is explicitly situated within a framework recognising multiplicative interactions among population, consumption, and technology (*cf.* IPAT/STIRPAT) and acknowledges rebound dynamics that can offset efficiency gains [2, 25]. Population is foregrounded because the empirical question concerns population time series and the $r \sim N$ relationship; this does not imply population-only causation or policy prescriptions.

Finally, the title refers to 'sustainable' carrying capacity, not a fixed biophysical ceiling. In peer-reviewed synthesis, sustainability requires that human demand remain within regenerative capacity over relevant time horizons, and overshoot implies reliance on stock depletion and waste accumulation [20, 23]. Given the documented global shift to a negative $r \sim N$ regime and long-standing evidence of global biocapacity deficit, the title is consistent with our definitions and with our conditional, caveated claims in the main text [2].

8. Conclusion

We concur with Haubrock [1] that mechanism identification and normative transparency are essential when discussing human carrying capacity. Nevertheless, his critique does not in any way overturn our principal empirical contribution: a historically abrupt and persistent global shift from facilitation to strong negative $r \sim N$ feedback quantified from population time series, consistent with emergent ensemble density compensation mediated by socio-economic, technological, and environmental constraints [2, 13–15]. Our sustainability benchmarks are explicitly conditional and aligned with established debates about carrying capacity and footprint accounting [23, 37, 45, 46]. Future work can extend these results using multivariate demographic-transition covariates and modern time-series techniques, but such extensions are complementary rather than refutations of the descriptive regime shift that we documented [3, 21, 22]. Nonetheless, we thank Haubrock [1] for drawing attention to our work and for the opportunity to clarify our argumentation, because planetary overuse and its implications for human population sizes are of growing importance in a world where ecological overshoot persists.

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), Writing – original draft (lead), Writing – review & editing (lead)

Melinda A Judge 0000-0002-9948-1865
Investigation (supporting), Writing – review & editing (supporting)

Daniel T Blumstein 0000-0001-5793-9244
Investigation (supporting), Writing – review & editing (supporting)

Aisha N Z Dasgupta 0000-0003-0945-137X
Investigation (supporting), Writing – review & editing (supporting)

Mathis Wackernagel 0000-0002-3659-1872
Investigation (supporting), Writing – review & editing (supporting)

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

Peter N Le Souëf 0000-0003-0930-1654
Investigation (supporting), Writing – review & editing (supporting)

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