Underestimating the risks of overpopulation endangers the health and lives of future children

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Abstract

The risks of climate change to children have been widely discussed, but the risks of overpopulation have not been similarly scrutinised. Projections of the health and mortality rates of infants and children have largely ignored overpopulation; for example, the United Nation's projections of infant mortality to 2100 disregard the influences of rapidly increasing populations in low- and middle-income countries and a deteriorating climate. In this paper, we first summarise the evidence that a large and growing human population will increase child mortality, and compromise health and wellbeing this century. Population growth increases the pace and magnitude of climate change because the degree of climate disruption is a product of per-capita consumption and total population size. Population growth also increases overcrowding, which in turn increases local and global air pollution, disease transmission, and resource scarcity, all of which have disproportionate effects on children compared to adults. To gain insight into the potential risks that children will face this century, we analysed the United Nation's *Medium* and *High* population projections for this century to show that between 9.91 billion and 14.49 billion children will be born from 2022 to 2100, and that most (> 60%) will be born in sub-Saharan Africa and Central/South Asia (6.19 billion and 9.10 billion, 62.5% and 61.4% of all births, *Medium* and *High* projections, respectively), where malnutrition is already high and capacity lowest to increase crop yields accordingly. We then identify areas where future child mortality can be expected to be higher than current predictions. We show that the lowest-income nations with the highest population growth have the fewest resources to protect increasing numbers of children from the deteriorating climate and the risks of overcrowding. We emphasise the urgent need for appropriate, quality, free, non-coercive, family-planning services to be universally available to allow men and women the opportunity to choose the size of their family. In summary, we provide the first evaluation of the evidence that overpopulation is already adversely affecting children and the evidence that there will be increasingly serious consequences for children if population growth continues at its current pace.

Key words: air pollution, child health, climate change, consumption, environment, overshoot, paediatrics, sustainability

Introduction

The health and wellbeing of children should be one of society's highest priorities, not just for children today, but also for children of the future. The demonstrated and potential effects of climate change on children's health have received considerable discussion (1-3) and many regional analyses, although only one analysis of its potential global magnitude (4). In contrast, the impact of human overpopulation on current children and the fate of future children is rarely discussed (5-7), and is mostly overlooked as a major factor affecting child health. This is evidenced by the current United Nations' projections of infant mortality to 2100 (8) that ignore the effects of a deteriorating climate and increasing population that will disproportionately affect children in the lowest-income nations (8, 9).

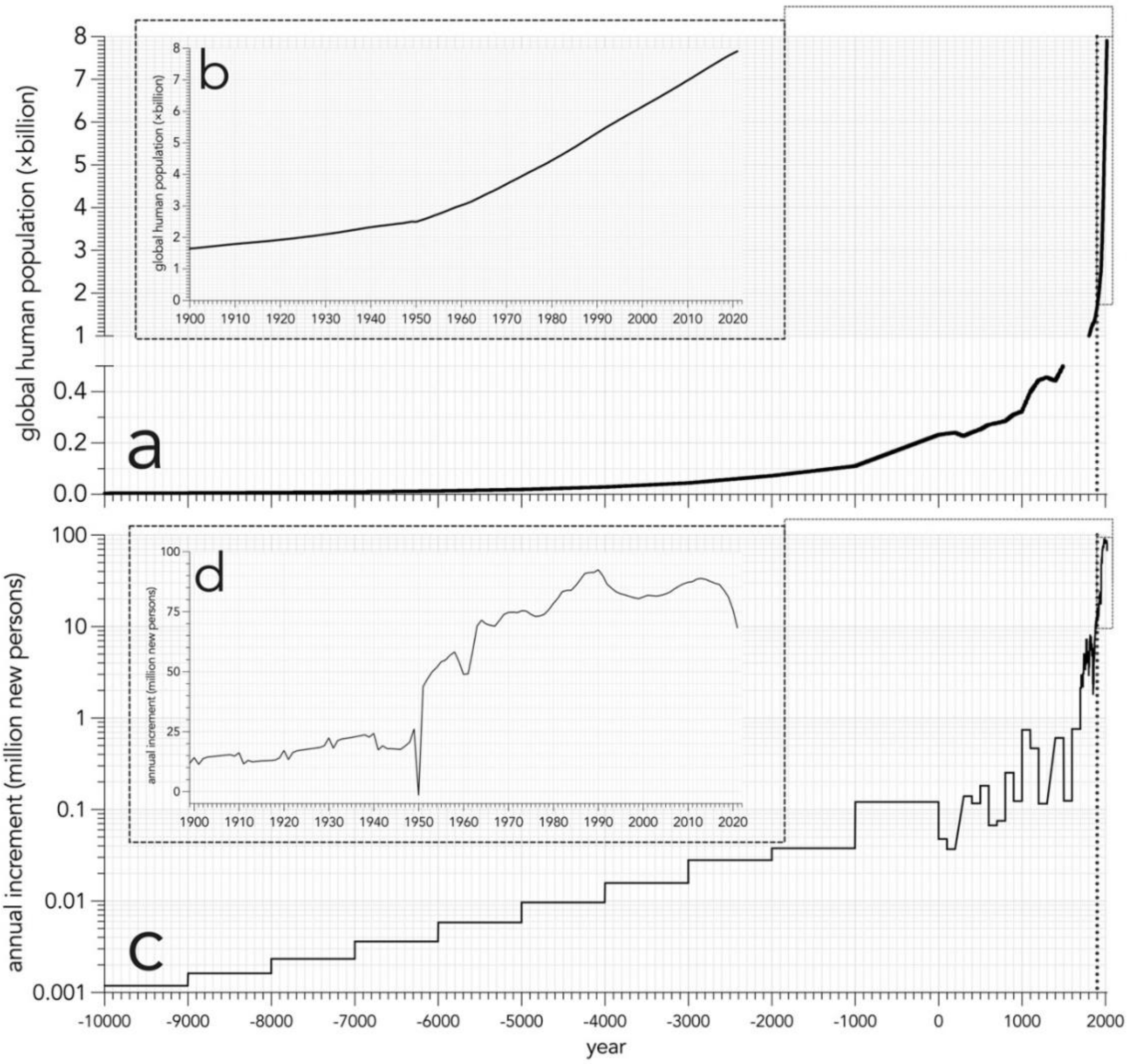
The required changes to protect the Earth's environment are now well-understood and include rapidly decarbonising the atmosphere (10, 11), preserving biodiversity (12-14), and protecting the natural environment (12, 15). The changes needed to protect children by slowing and then reversing human population growth have received less attention, even though an important component is the provision of universal, freely available, voluntary, socially and culturally appropriate, and quality family-planning services (5, 16, 17), as enshrined in the United Nation's Sustainable Development Goal 5. A better appreciation of the threats facing future children is important to catalyse governments, policy makers, non-government organisations, and human society in general to commit to the changes needed to address both climate change and overpopulation.

The aim of our paper is therefore to provide the first summary of the existing evidence that overpopulation has already affected children's health. We then use published projections of population growth to provide evidence that a large and growing human population threatens the health and wellbeing of an increasing number of children as this century progresses.

Quantifying the global increase in population

Since civilisation began, human societies have developed new technologies allowing rapid environmental exploitation and a commensurate population expansion. The size of the global human population was around 7 million 12,000 years ago (18, 19) (Fig. 1), and for the next 8,000 years, grew at an average per-capita rate of 0.0237% $year^{-1}$ to reach 232 million by year 0 AD (20) (Fig. 1). This rate progressively increased from year 0 to the current rate of 0.9% per year (19), which is more than 36 times higher and modifies a population that is over 1000 times larger than it was 12,000 years ago. Regardless, many global authorities have asserted that the world's population growth rate is slowing (19, 21), but this deceptively reassuring conclusion ignores that the decreasing component is the *per capita* rate — that since 1981, the number of new people added to the population has remained > 80 million *each year* until COVID intervened in 2020 (22) (Fig. 1). To put this in perspective, for the last four decades, the world population has increased by more than the world's entire population 12,000 years ago *every five weeks*. This 'overshoot' has strained on our planet's capacity to provide for the current human population (23), with children especially vulnerable to the environmental consequences (24, 25)

Figure 1: (a) Trajectory of the global population over the last 12,000 years (source: ourworldindata.org). (b) Inset shows the trajectory from 1900–2022. (c) Number of new persons added each year to the world population since 10,000 BCE. (d) Number of new persons added each year from 1900–2022.



Population growth has strained the planet's biocapacity

In 1992, Rees (26) described the concept of the 'ecological footprint', and calculated that humans were taking around 60% more from their environment than the environment could sustain. With an increasing population, this percentage has risen to 71% (27) and this 'ecological overshoot' causes major damage to every aspect of the natural environment (15, 28). The changes might already be irreversible (29-31), but there is agreement that even if strong action is taken immediately, the global climate will inevitably become more hostile over the coming years (30, 31). In short, our planet's ability to sustain a healthy existence for an increasing number of children and adults was passed long ago, yet our population continues to increase (5, 29).

'Overpopulation' can be defined several ways, but in general occurs when the number of individuals of a given species exceeds the number its environment can sustain (32). There is still no universal agreement that the planet is overpopulated, with dissenters from the United Nations (33), science communication (34-36), and even scientists (37). Such 'overpopulation denialists' (38) emphasise the ability of the planet to continue to feed its populace (35, 37) and ignore the short-term nature of their arguments (35), as well as the continuing destruction of the biosphere and accelerating extinction of species (39). In contrast, Rees's (26) carefully considered thesis and focus on rising per-capita resource consumption, especially in wealthy countries (13), along with mounting environmental destruction (15), identify that overpopulation is a real problem and challenge (7, 15, 40). Reasons why overpopulation has received little attention (5-7) could be that society tends to ignore "… data that do not fit with its myths and metaphors" (41, 42).

Addressing inequity and global justice are paramount for securing the future of children, as is recognising that high-income nations are responsible for most global consumption while being simultaneously the least vulnerable to its consequences (43). The effect of global overpopulation on environmental integrity is largely due to the activities of high-income countries, so it follows that reductions in both consumption and population size are important components of reducing environmental damage (5, 44). For low- and middle-income nations, adhering to the United Nation's Sustainable Development Goal 5 would help insulate future generations of children from the consequences of environmental decay and limited health resources in response (45). Reducing infant mortality is also an important aspect of reducing fertility rates in low- and middle-income countries (46). Equitable sharing of sustainable natural resources among all nations (47) would also reduce poverty and hence, infant mortality and fertility in poorer countries (46). The economic circumstances of nations vary greatly, but the need to reduce population growth and reverse trends applies to all societies (5). Warnings that an aging society resulting from reducing global population will have serious adverse consequences on humanity have been proposed without supporting evidence to the contrary (28).

Why humans have done so much to improve their own situation in the short term, but so little to stop damaging the planet in the long term, is a valid question. The contribution of an increasing global population to environmental damage is now well-established (15, 23, 28)(48). Population size is an inherent component of climate change, because environmental impact is the product of per capita consumption and population size. Consumption is also driven by economic factors described in the full report of the Sixth Assessment of Intergovernmental Panel on Climate Change (IPCC) (44), which stated unequivocally that: "Globally, gross domestic product (GDP) per capita and population growth remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade". Why population size was not mentioned in the IPPC's summary report (30) or in that of the 27th Conference of the Parties in 2022 (11) is unclear, but could reflect the global reluctance to address overpopulation (6, 41). The relationship between population size and climate change is by no means simple given the inequities in individual and national resource consumption, access to resources, and economic capacity (49, 50). If the global human population had stabilised at one or two billion (below the estimated maximal sustainable global footprint) (51), climate disruption would not have occurred, or at least it would have been of lower magnitude and progressed at a slower rate (31).

Although the climate-change component of environmental damage has received widespread attention and calls for action, greenhouse-gas emissions (both total and per-capita) have continued to rise almost linearly (52), which not even the COVID-19 pandemic could slow (52-54). The rapid rise in renewable energy has also not slowed this increase, a poignant demonstration of Jevon's paradox (55) — increasing efficiency in resource use tends to increase the total use of that resource. Regardless of how we generate energy, more energy consumption is likely to increase environmental damage (31), making the planet less hospitable for children. In short, the evidence that too many humans are taking too much from the planet is irrefutable, yet our total population and consumption continue to increase much as they have over the last 50 years, and efforts to change these trajectories have had little discernible effect.

Overpopulation is already adversely affecting children's health

Major scientific and humanitarian advances have reduced infant and child mortality over recent decades (13, 56), although high mortality still occurs in low- and middle-income countries (8). Escalating environmental damage and climate change, combined with an increasing population, now threaten to reverse these improvements (1, 44). Whereas high-income countries have the resources to insulate children from some of the immediate threats, this might not be the case with further environmental deterioration. In the following sections, we summarise why low- and middle-income nations with fewer resources and higher populations are already less able to provide a healthy environment for children, and will be less able to do so in the future (57-59).

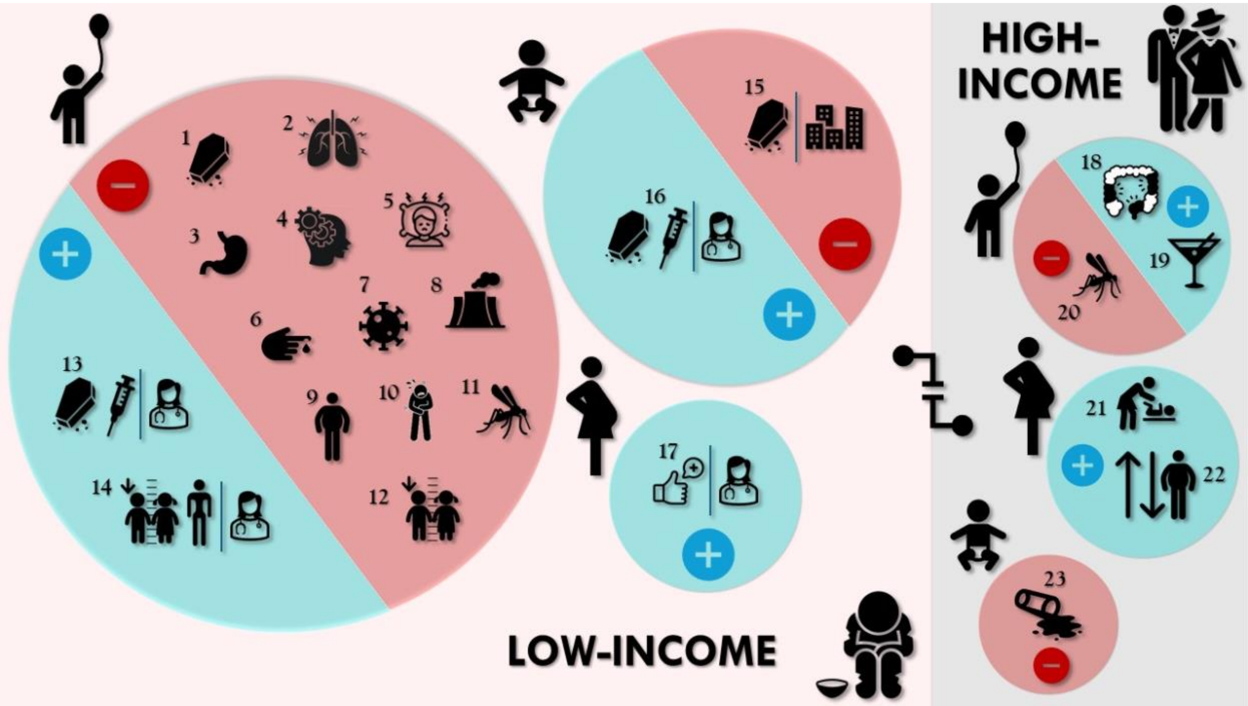
The consequences of overpopulation are already worsening children's health and wellbeing. Within the family unit, too many children for the family's space or resources strain a family's economic capacity to care for the health of their children. Indeed, overcrowding measured by household size is associated with a higher rate of childhood mortality in African nations (60). At an urban scale, rapid urbanisation and overcrowding are also associated with increases in the risk of developing infectious diseases (61), and communicable (62) and non-communicable diseases (63, 64).

City size correlates with population density (65, 66), and although relationships are complex and affected by local factors (66), population density correlates with air pollution in both low- (67) and high-income (66) countries. City size has a strong influence on air quality in low- and middle-income countries (66, 67). The five African cities with the highest populations also have the highest concentrations of (particulate matter) $PM_{2.5}$ (67). Mega-cities in India are among the most polluted cities in the world (68). The correlation between city size, population density, and air pollution is concerning, because air pollution is a major cause of childhood respiratory disease (69) and mortality (57). For each 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$, there is a 9% (95% confidence interval: 4–14%) rise in infant mortality in African countries (57). Nigeria, Democratic Republic of the Congo, and Ethiopia with high population growth had more people exposed to poor air quality in 2019 despite reductions in the use of solid fuels for cooking (67). Overall, air pollution in Africa caused an estimated 449,000 additional infant deaths in 2015 (57).

The spread of non-communicable and infectious diseases is facilitated by household overcrowding that increases with urbanisation (70). Although initially benefitting children by increasing the availability of health services (71) and reducing the prevalence of undernutrition (64), rapid urbanisation (a surrogate for high population density) increases the incidence of chronic diseases by adulthood (64), aids the rapid transmission of infectious disease (71), and is associated with increases in many infectious diseases, including pneumonia (61), diarrhoea (72), malaria (73), tuberculosis (74), yellow fever (75), Ebola (76), HIV (77), cholera (78), and many zoonotic diseases including COVID-19 (79). Hence, overpopulation not only inhibits growth in children, but also increases the conditions arising from breathing polluted air, most infectious diseases, and potentially more pandemics.

To evaluate how population density affects child health in greater detail, we examined the published evidence for this relationship. A literature search using the terms "population density" OR "overpopulation" & "child health", between 2015 and 2024, identified 40 papers showing an effect of population density on child-health outcomes. A summary of results is shown in Fig. 2 and the full review is available in Supplementary Appendix 1. There is evidence for many aspects of child health being eroded by increasing population density, but there was a clear distinction between lower- and higher-income countries. High population density in lower-income countries is linked to both negative and positive child health outcomes; however, every positive child health outcome was facilitated by increased access to healthcare rather than a direct benefit from population density itself. Those directly related to population show increasing density worsened child health in lower-income countries. Because most future children will be born in developing countries, there is a disproportionate negative effect of higher population densities on most children worldwide. Population density also had mixed effects on child health in higher-income countries; however, it appears that these children are buffered from many of the worst health outcomes.

Figure 2. Effects of population density on child, infant, and maternal health.



legend

Low-income nations (left panel)	
Negative effects (red) on children	**1**. ↑ mortality; **2**. ↑ respiratory disease; **3**. ↑ gastrointestinal/enteric disease; **4**. ↓ cognitive ability; **5**. ↑ sleep disorders; **6**. ↑ diabetes; **7**. ↑ COVID; **8**. ↑ air pollution & resultant disease; **9**. ↑ body mass index; **10**. ↑ typhoid; **11**. ↑ vector-borne disease (e.g., dengue): **12**. ↑ stunting
Positive effects (blue) on children	**13**. ↓ mortality & ↑ vaccination rate due to ↑ health care; **14**. ↓ stunting/wasting/underweight due to ↑ health care
Negative effects on infants	**15**. ↑ mortality due to ↑ urbanisation
Positive effects (red) on infants	**16**. ↓ mortality & ↑ vaccination rate due to ↑ health care
Positive effects (blue) on pregnant women	**17**. better maternal outcomes due to ↑ health care
High-income nations (right panel)	
Positive effects (blue) on children	**18**. ↓ irritable bowel syndrome; **19**. ↓ binge drinking
Negative effects (red) on children	**20**. ↑ zoonotic disease transmission
Positive (or equivocal) effects on pregnant women	**21**. ↓ teenage pregnancy; **22**. ↑ or ↓ body mass index
Negative effects (red) on infants	**23**. ↑ fungal contamination of human milk

Larger populations will adversely affect all future children

Despite high-income countries having more capacity to buffer children from future shocks, overcrowding can reduce access to green space and erode mental health and wellbeing (80-82), increase pre-term births (83), harm lung function (80), and lead to more respiratory diseases (84). Australia is an example of a high-income nation with high net immigration; overall, its population growth exceeded 1.5% year^{-1} prior to the COVID-19 pandemic (85), and increased to 2.4% thereafter (86). Australia, like many resource-rich countries, relies on immigration to maintain and expand its economy, and its population will more than triple by the end of the century if the current growth rate continues (85, 87). Feeding > 70 million people will be difficult given that Australia currently produces food for around 60 million people (88), a precarious situation given the country's relatively infertile and fragile soils (89, 90) and the compounding negative effects of climate change on crop yields (91-93)(94). Australia might therefore be unable to feed its own population by 2100 (88). This would have serious consequences, because it currently exports 72% of its food production (95) and would cease its role as a major global food supplier by 2050 (92, 94).

With projected increases in the global population, food supply will need to increase by between 50 and 70% by 2050 to maintain the current nourishment supply worldwide (93), even though this supply (or at least, its equitable distribution) is already inadequate (96, 97). This increase will require 70 million hectares of additional land for planting crops (96), which will be lower-quality and require more resources to maintain yields (including irrigation), thereby eroding biodiversity further (39). Whether such an increased rate of production is possible in the face of climate change is uncertain because yields will also decline with warming (98-102). Because 80–90% of irrigation potential is already realised, expansion is limited in the face of potential reductions in precipitation (96). Technology has slowed the time to reach the point where food demand outstrips available arable land, leading some to downplay (35) or disregard whether this will occur (35, 36). The 'green revolution's' improvements in agricultural technology aimed to reduce undernourishment by striking a balance between growth in population and food production (103), but the recent increase in undernourishment and the lack of additional arable land suggest that this aim can no longer be met (104). This situation is not helped by meat consumption continuing to increase (105), despite the higher environmental costs of its production (105). Based on current evidence, avoiding further increases in malnutrition and stunting in young children, with its associated increases in child mortality from other diseases (106, 107), will be difficult to avoid.

Children in low- and middle-income nations will be most affected by future increases in population because they live in the places where population growth is highest (108), the environment is most fragile, agricultural production is the lowest (109), and economic resources to address these issues are most limited. Indeed, a study examining child-health data from every African country demonstrated that environmental degradation (110) driven by high population growth rates impairs child health (60). However, the predicted scale and nature of future impacts will depend on many interacting factors, including the success of interventions to reduce environmental damage, economic development, national and international environmental policies, and public-health initiatives.

If the availability of the resources required to maximise health does not increase proportionally to population growth, the average health of children will decline. The number of undernourished people worldwide had been gradually reducing to an estimated 573.3 million in 2017, but then increased to 767.9 million in 2021, a 33.9% increase in 4 years (104); the latest estimates that include effects of the COVID-19 pandemic place the number as high as 828 million (104). The Food and Agriculture Organization's recent report also estimates that that the COVID-19 pandemic added 79 million people to the previous estimates of those undernourished (104). The United Nations International Children's Emergency Fund estimated in 2022 that stunting was present in 22.3% of children under 5 years of age globally, and in 33.5%, 28.1%, 8.3%, and 4.0% in low-, lower-middle, upper-middle, and high-income countries, respectively, and 31.5% of children in sub-Saharan Africa (111). Their reports have expressed concern regarding Sustainable Development Goal 2.2 relating to eradicating stunting (13, 99).

The World Health Organization has estimated that malnutrition is responsible for 45% of all childhood deaths in low- and middle-income countries (112, 113), because malnutrition increases mortality from infectious diseases, especially acute respiratory infections (106, 107). Malnutrition in parts of sub-Saharan Africa is also a driver of low educational status and economic damage (102), and both these outcomes will feed back to erode children's health (102).

Relationships between overpopulation, climate change, and child health

The number of children adversely affected by climate change will increase not only because there will be more children, but because of the increasing number of vulnerable children (114-116). The latest Intergovernmental Panel on Climate Change report states with "very high confidence" that climate change has already harmed children's health, including most aspects of their physical and mental health (2, 117). Indeed, a deteriorating environment will have adverse effects of on most organ systems (118) — rising ambient temperature and more frequent and intense heat waves, as well as worsening air pollution increase medical problems in children (119). The effects of climate change on children's health has been summarised recently in the first meta-analysis of all available published evidence (4). The greatest effects were in increases in preterm births and respiratory disease (4). Individual studies have also shown increases in preterm births (120-122), as well as respiratory infections (123, 124), asthma (114, 115, 125, 126), kidney damage (127, 128), diabetes (129-132), diarrhoeal diseases (125, 133, 134), malaria (135), presentations to emergency departments (126, 136-138), heat stroke, organ failure (139, 140), and mental health problems (119, 141). Even more concerning, the concentration of atmospheric CO_2 expected by 2100 could directly damage mammalian brain and respiratory development prior to birth (142, 143).

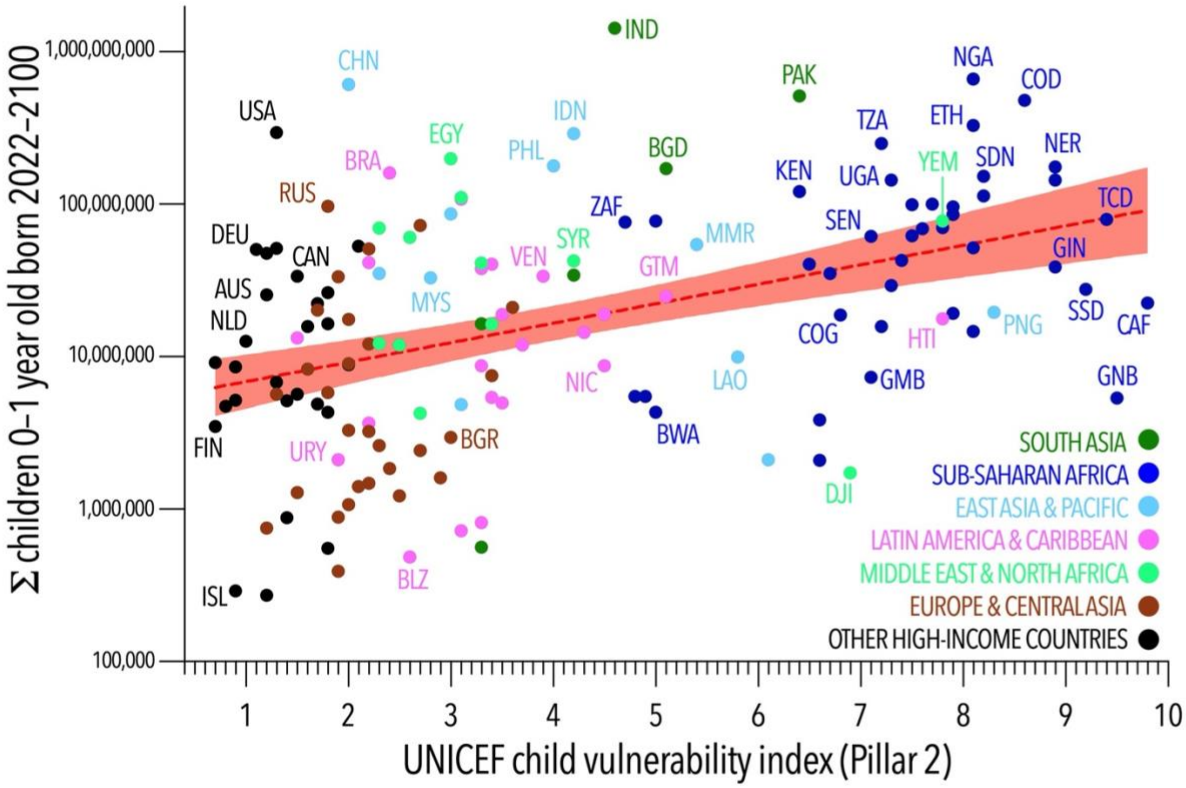
Adverse perinatal outcomes worsen with climate change. The risk of preterm birth is already higher in low- and middle-income countries (120, 144) and is projected to increase (144). Globally, the risk increases with ambient temperature and heatwaves (4, 83, 122, 144, 145), and with lower socio-economic status (120). Preterm birth is a major contributor to infant mortality and lifelong health problems, including neurological impairment, chronic respiratory impairment, reduced growth, and other disorders (144, 146). Little is known about the pathophysiological mechanisms by which high temperatures increase preterm births, but a thermoregulatory problem in pregnant women exposed to extreme heat resulting in aberrant inflammatory responses has been proposed (147), and cortisol-induced uterine activity due to prostaglandin release has also been postulated (120, 147). More research to improve understanding of these mechanisms to develop strategies to mitigate the risk is required (147). In the meantime, resources are already scarce for maintaining children's health in low- and middle-income nations (1, 144), so a rapidly increasing population combined with climate change will *ipso facto* exacerbate preterm birth rates and further increase infant and child mortality (144).

Children's respiratory health is particularly vulnerable to overpopulation and climate change (66, 67, 69, 106, 107). Globally, high temperatures increase the risk of respiratory disease in children (4). In Indonesia, Brazil, and India, high humidity increases the prevalence of childhood pneumonia (148). Pollutant exposure associated with climate change correlates with an increase in the prevalence of asthma, atopic dermatitis, and allergic rhinitis (149, 150). Air pollution is responsible for an estimated 236,000 deaths in the first month of life of newborns in Africa, and with 14% of all deaths in children under the age of 5 across that continent (67). Extreme temperature exposure and heat waves have also been associated with increased paediatric presentations to hospital for asthma in Australia (152), USA (119, 152), and South Africa (116). Child health will deteriorate as the climate changes, but this relationship is complex and influenced by many confounding factors, such as existing local climate conditions, infrastructure, and socio-economic status (153, 154).

Climate change already strains systems that are essential for maintaining good child health, but particularly on those unable to cope with current numbers of children (1). Climate change also reduces food security (94), forces migration (155), and increases conflict (156). The latter leads to malnutrition, fewer educational opportunities for children, and more barriers to receiving health care (156). For every 1 °C increase in temperature, wheat production is expected to decline by 6% (157); hence, climate change and a rising population will increase the number of children suffering from malnutrition. In Ethiopia, a 1 °C increase in average ambient temperature during pregnancy is associated with a 28% rise in the risk of developing stunting during early life (158). This could be explained, at least in part, by temperature-driven reduction in crop yields that weaken food security integral to sustaining maternal and neonatal nutrition. Low- and middle-income nations that already have poor food security will be at greater risk of facing the poor health outcomes associated with climate change.

To examine the susceptibility of future children to climate change, we examined the relationship between the numbers of children born in each country for the remainder of the century and the children's climate risk index (159, 160) (Fig. 3). There is a positive relationship between countries with the most children predicted to be born up to 2100 and a higher child climate risk index (Fig. 3). This shows that, in general, countries where the climate risk is highest are those with the greatest numbers of children born.

Figure 3. Number of children < 1 years old expected to be born and survive between 2022 and 2100 compared to the UNICEF child vulnerability score.

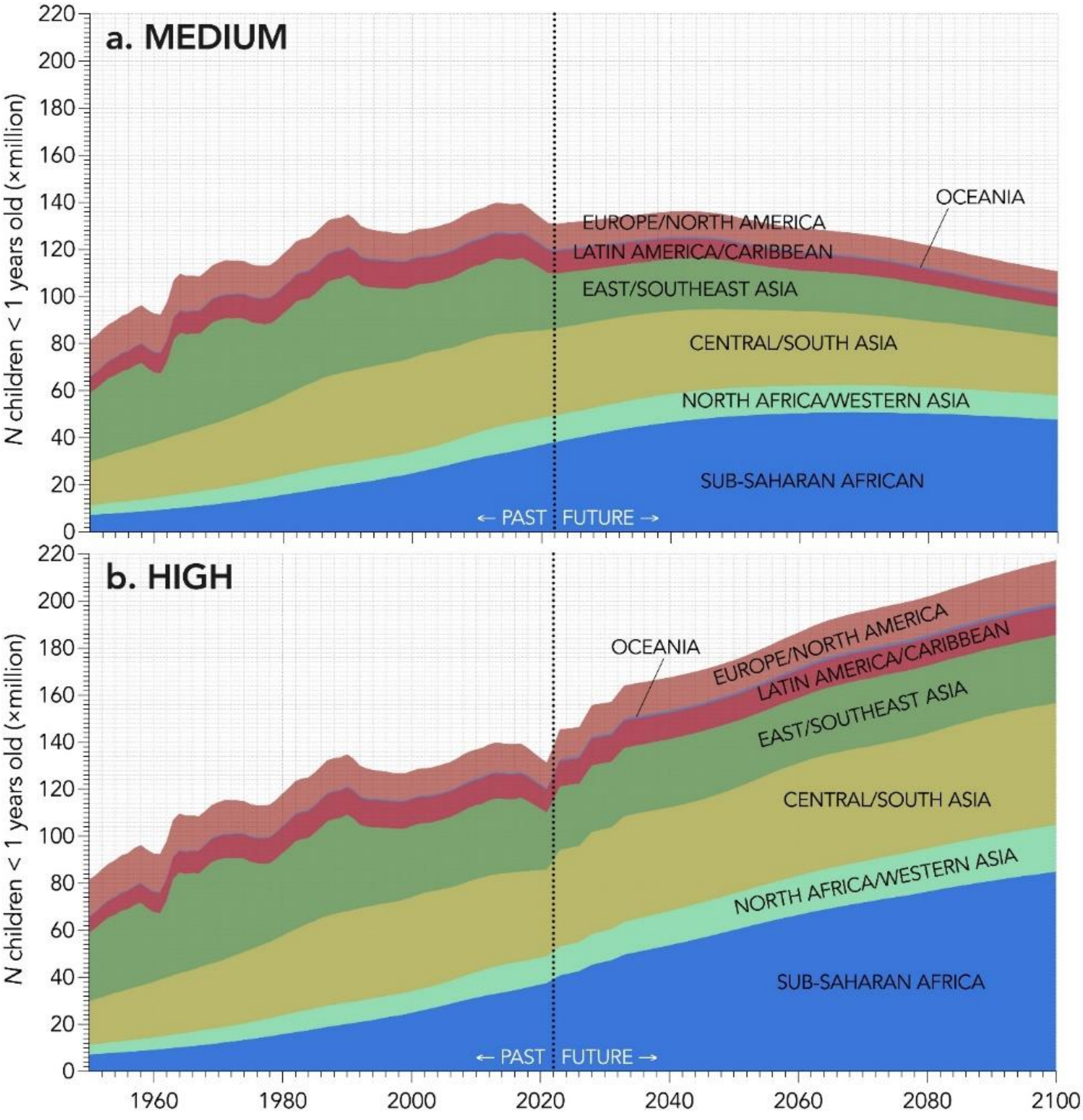


Country codes shown: AUS = Australia, BGD = Bangladesh, BGR = Bulgaria, BWA = Botswana, BRA = Brazil, BLZ = Belize, CAF = Central African Republic, CAN = Canada, CHN = China, COD = Democratic Republic of Congo, COG = Republic of Congo, DEU = Germany, DJI = Djibouti, EGY = Egypt, ETH = Ethiopia, FIN = Finland, GIN = Guinea, GMB = Gambia, GNB = Guinea-Bissau, GTM = Guatemala, HTI = Haiti, IDN = Indonesia, IND = India, ISL = Island, KEN = Kenya, LAO = Laos, MMR = Myanmar, MYS = Malaysia, NER = Niger, NGA = Nigeria, NIC = Nicaragua, NLD = Netherlands, PAK = Pakistan, PHL = Philippines, PNG = Papua New Guinea, RUS = Russia, SDN = Sudan, SEN = Senegal, SSD = South Sudan, SYR = Syria, TCD = Chad, TZA = Tanzania, UGA = Uganda, URY = Uruguay, USA = United States, VEN = Venezuela, YEM = Yemen, ZAF = South Africa.

Most children born this century will live in the poorest regions

To quantify the scale of the problem that increasing population growth will have on future children, we calculated the number of infants projected to be born this century and the regions and countries where they will be born. We used open source projections for this century produced by the United Nations (22) for all projections. The United Nations' *Medium* and *High* population growth models (161) predict 9.91 billion and 14.49 billion children, respectively will be born globally between 2023 and 2100 (Fig. 4). For comparison, there were 134 million children born globally in 2021 (162), and there were 2.01 billion children aged 0–14 years in the world in 2022 (163).

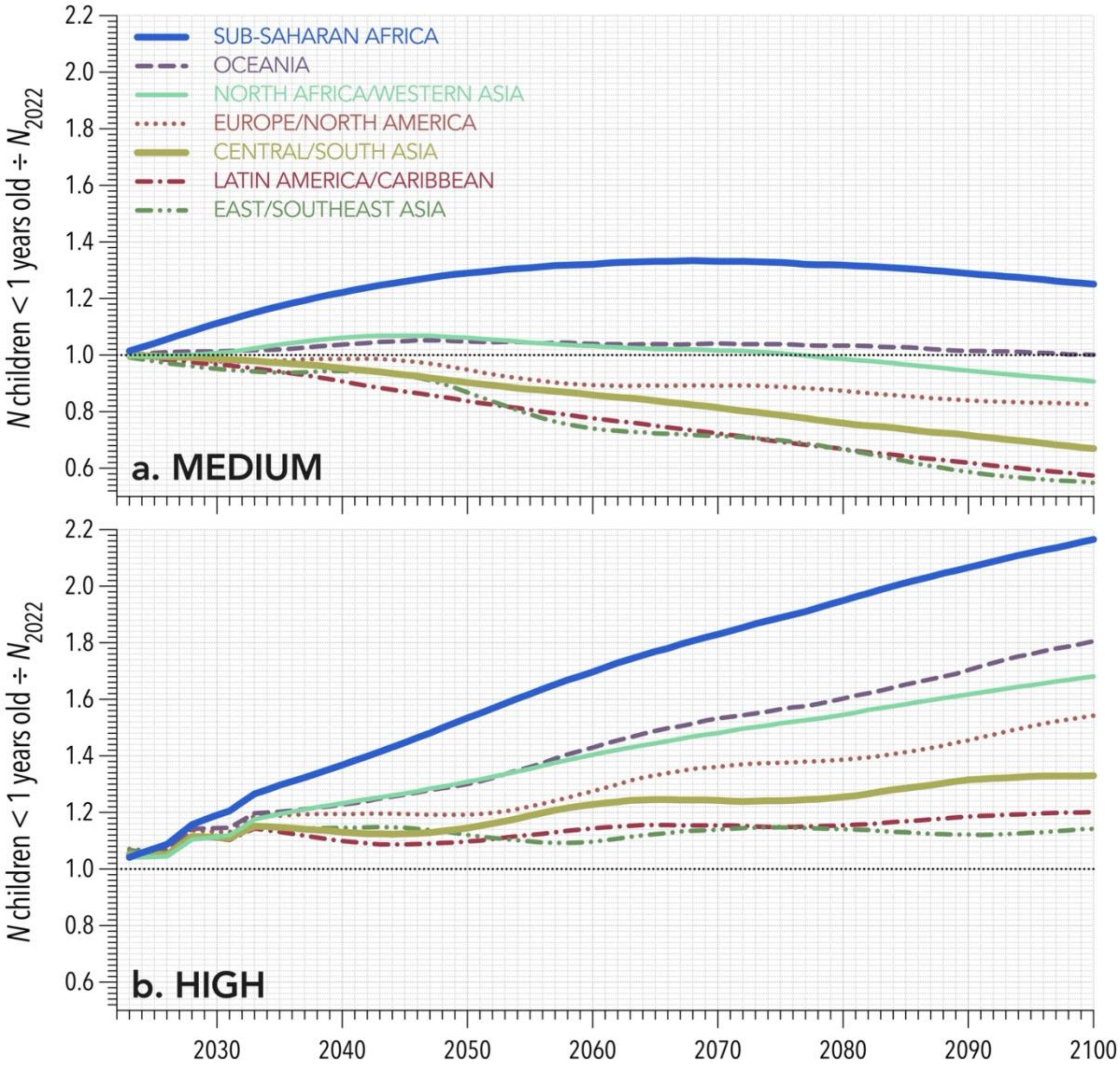
Figure 4. Annual numbers of children < 1 years old expected to be born between 2022 and 2100 for each world region for the United Nations' *Medium* (a) and *High* (b) growth models.



The region with the highest number of births is sub-Saharan Africa, where between 3.75 billion (*Medium*) and 5.13 billion (*High*) children are predicted to be born by 2100 (Fig. 4), followed by Central/South Asia (2.44 billion to 3.67 billion, respectively), East/Southeast Asia (1.41 billion to 2.22 billion), North Africa/Western Asia (0.89 to 1.29 billion), Europe/North America (0.78 to 1.19 billion), Latin America/Caribbean (0.58 to 0.90 billion), and Oceania (0.06 to 0.09 billion).

Sub-Saharan Africa is by far the poorest region in the world (162), where 22 (45.8%) of the 48 countries therein are classified as ‘low-income’ and 41 (85.4%) are classified as low- or lower-middle income. Sub-Saharan Africa also includes 22 of the world’s 26 low-income countries (164). The region where the highest number of children will be born this century is also by far the poorest (see also Fig. 5). With the forecasted numbers of children in the poorest regions, there is no consideration in the United Nation’s infant mortality projections for increasing mortality due to the consequences of not being able to feed these additional children (8). The problem for children in regions such as sub-Saharan Africa is not just in increased numbers to feed, it also includes the consequences of the projected decrease in crop yields as the climate deteriorates this century (98-102).

Figure 5. Projected annual ratio of children < 1 years old born to number of children < 1 years old born in 2022 for each world region based on the United Nations’ *Medium* (a) and *High* (b) growth models. Horizontal black dotted line indicates a ratio = 1.

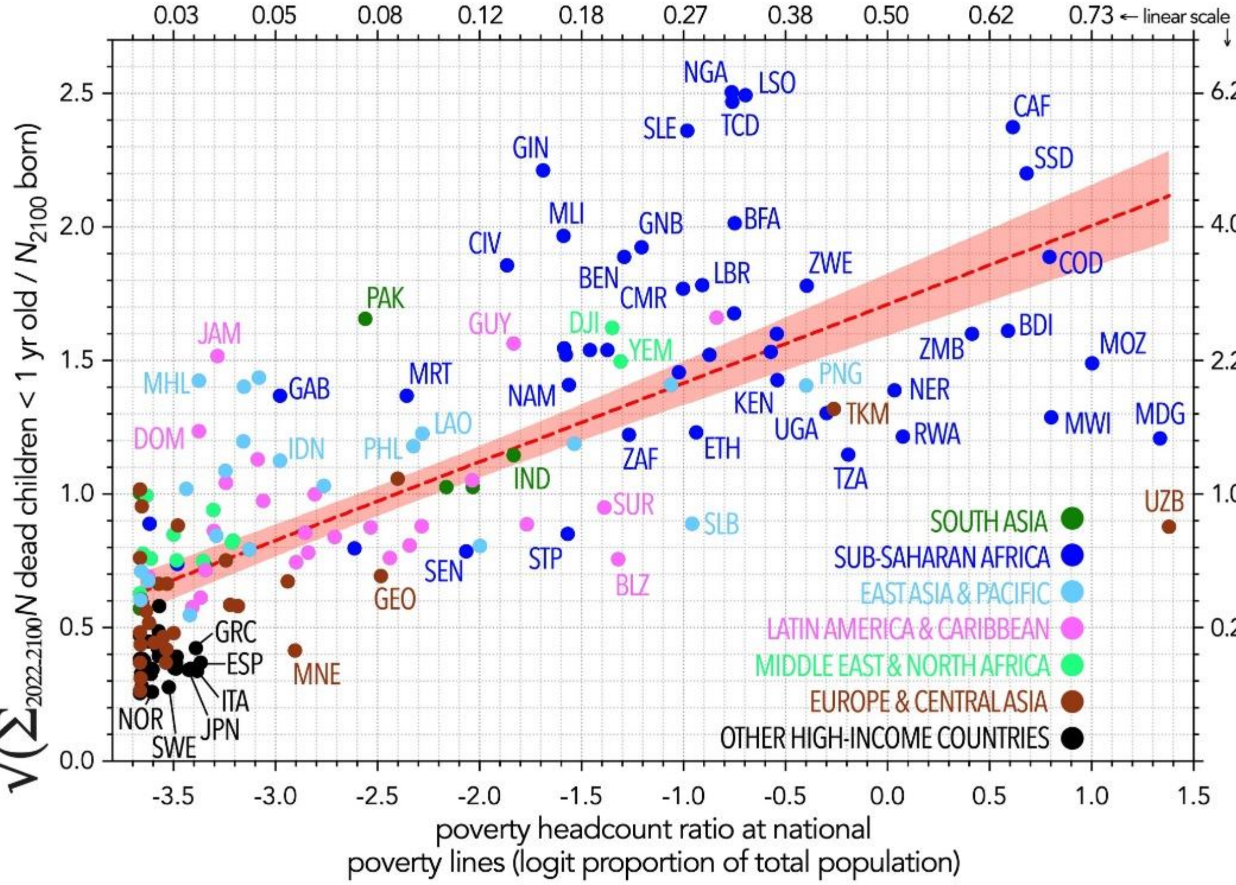


Interrelationships between population increase, poverty, and infant death

Poverty is a well-established predictor of infant and child mortality (165-168), so to determine which regions will have the highest burden of child mortality, we need to control for relative poverty among nations. Further, larger populations will *ipso facto* produce more child mortalities over any time frame, so we also need to correct for population size when comparing regions or nations for the future burden of child mortality.

We obtained national poverty data from the World Bank (data.worldbank.org), measured as the poverty headcount ratio at national poverty lines (i.e., proportion of the population living below national poverty lines for the most recent available year for each country, expressed on the logit scale to linearise the data). We then summed the projected number of child (0–1 year old) mortalities from 2022 to 2100 from United Nations World Population Prospects 2022 (number of deaths by single age) under the *Medium* projection variant (population.un.org/wpp). We divided the sum of projected child (0–1 years old) deaths from 2022 to 2100 by the number of 0–1-year olds projected to be born in 2100 by country to control for relative population size (expressed on the square-root scale to linearise the data). Figure 6 shows the relationship between the population size-standardised total number of child deaths as a function of national poverty.

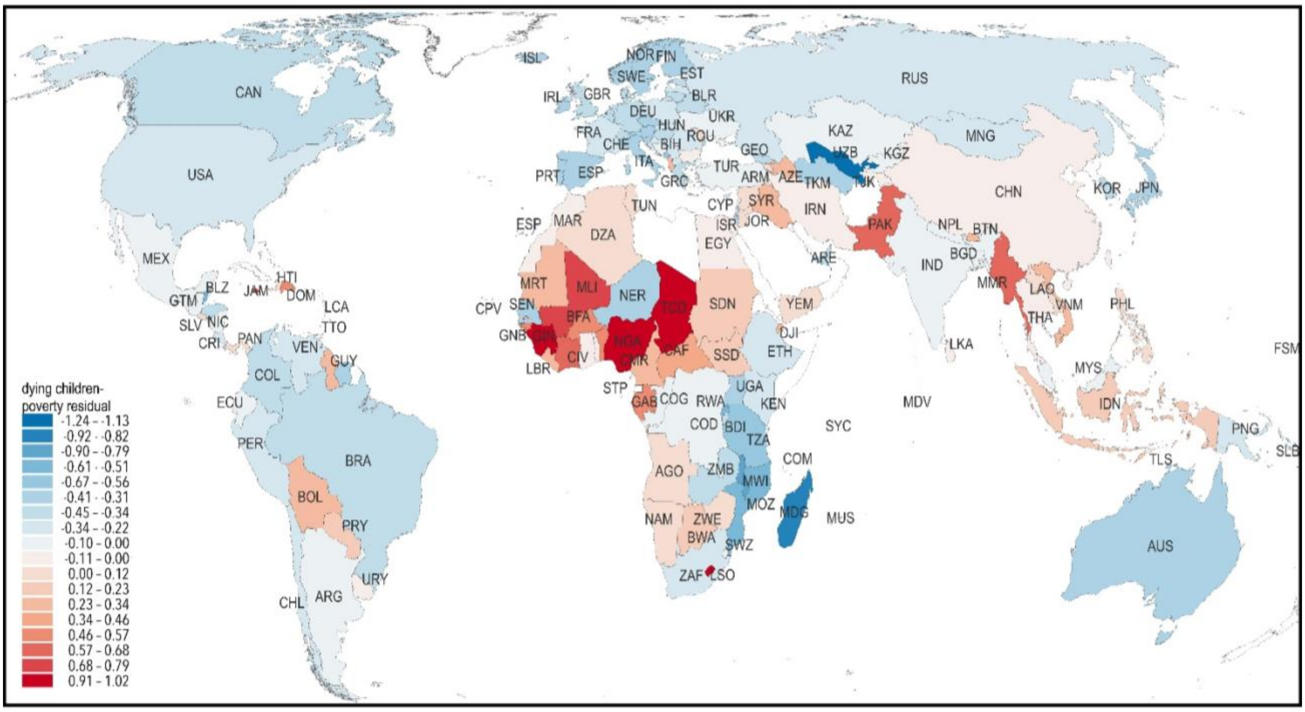
Figure 6. Relationship between population size-standardised child mortality (0–1 year old; square-root scale) and national-scale poverty (logit proportion of total population). Also shown are the equivalent linear scales for the *x* (upper axis) and *y* axes (right axis).



Country codes shown: BDI = Burundi, BEN = Benin, BFA = Burkina Faso, BLZ = Belize, CAF = Central African Republic, CIV = Côte d'Ivoire, CMR = Cameroon, COD = Democratic Republic of Congo, DJI = Djibouti, DOM = Dominican Republic, ESP = Spain, ETH = Ethiopia, GAB = Gabon, GEO = Georgia, GIN = Guinea, GNB = Guinea-Bissau, GRC = Greece, GUY = Guyana, IDN = Indonesia, IND = India, ITA = Italy, JAM = Jamaica, JPN = Japan, KEN = Kenya, LAO = Laos, LBR = Liberia, LSO = Lesotho, MDG = Madagascar, MHL = Marshall Islands, MLI = Mali, MNE = Montenegro, MOZ = Mozambique, MRT = Mauritania, MWI = Malawi, NAM = Namibia, NER = Niger, NGA = Nigeria, NOR = Norway, PAK = Pakistan, PHL = Phillipines, PNG = Papua New Guinea, RWA = Rwanda, SEN = Senegal, SLB = Solomon Islands, SLE = Sierra Leone, SSD = South Sudan, STP = Sao Tome and Principe, SUR = Suriname, SWE = Sweden, TCD = Chad, TKM = Turkmenistan, TZA = Tanzania, UGA = Uganda, UZB = Uzbekistan, YEM = Yemen, ZAF = South Africa, ZMB = Zambia, ZWE = Zimbabwe

As hypothesised, there is a strong relationship ($R^2 = 0.54$) between the number of projected child deaths and poverty (Fig. 6). However, the more interesting outcome of this relationship is where individual countries sit relative to this expected positive relationship — countries with high positive residuals (above the line of best fit) are predicted to experience many more child deaths over the remainder of the century than their poverty or population size would otherwise predict, whereas those countries with negative residuals (below the line of best fit) are predicted to have far fewer child deaths than their poverty or population size would otherwise predict. Countries such as Nigeria, Chad, Lesotho, Guinea, Sierra Leone, Central African Republic, South Sudan, and Pakistan have much higher predicted child deaths than their poverty or population sizes would otherwise predict. In contrast, countries like Uzbekistan, Mozambique, Madagascar, Rwanda, Malawi, and Tanzania have much fewer (visualised spatially in Fig. 7).

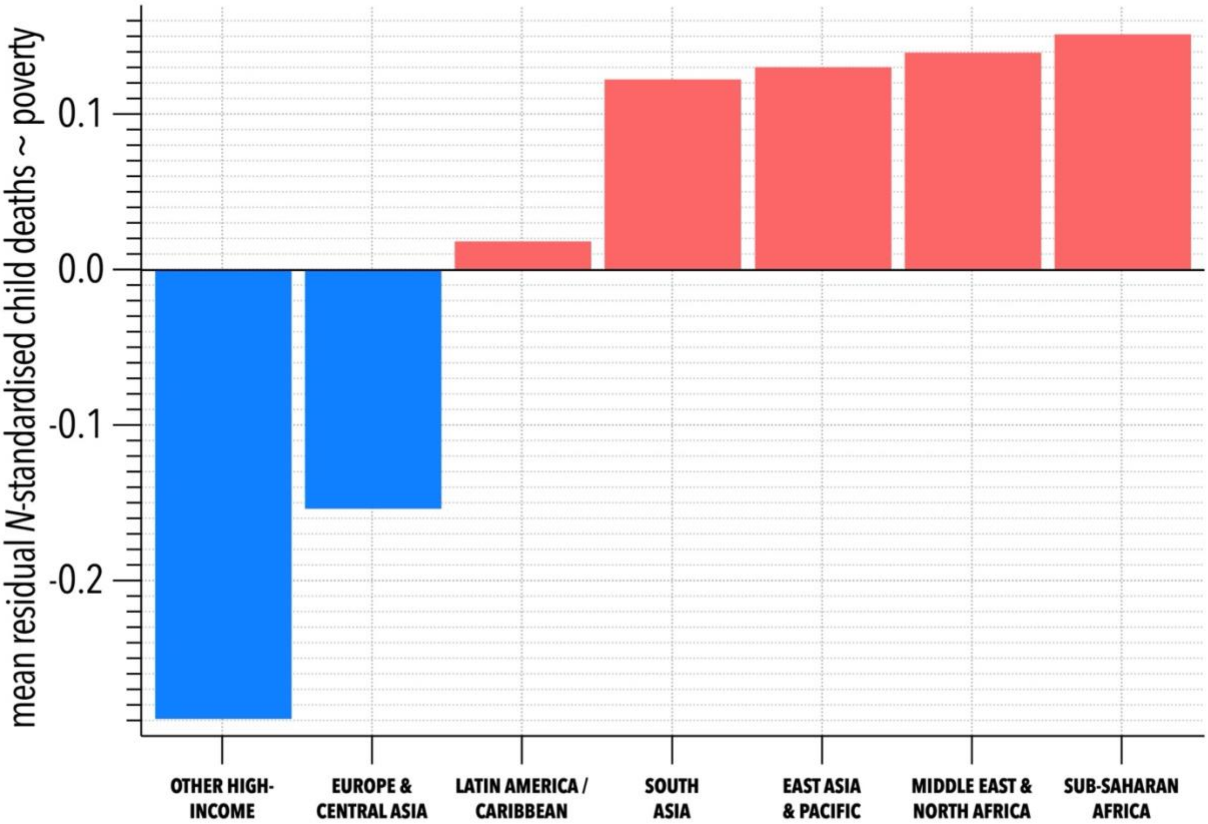
Figure 7. World map of the residuals from the relationship in Fig. 6 – the redder the colour, the higher the poverty- and population-standardised child mortality; the bluer, the lower the poverty- and population-standardised child mortality (see residuals in Fig. 6).



Country codes shown: AGO = Angola, ARG = Argentina, ARE = United Arab Emirates, ARM = Armenia, AUS = Australia, AZE = Azerbaijan, BDI = Burundi, BEN = Benin, BFA = Burkina Faso, BGD = Bangladesh, BIH = Bosnia and Herzegovina, BLR = Belarus, BLZ = Belize, BOL = Bolivia, BRA = Brazil, BTN = Bhutan, BWA = Botswana, CAF = Central African Republic, CAN = Canada, CHE = Switzerland, CHL = Chile, CHN = China, CIV = Côte d'Ivoire, CMR = Cameroon, COD = Democratic Republic of Congo, COG = Congo, COL = Colombia, COM = Comoros, CPV = Cabo Verde, CRI = Costa Rica, CYP = Cyprus, DEU = Germany, DJI = Djibouti, DOM = Dominican Republic, DZA = Algeria, ECU = Ecuador, EGY = Egypt, ESP = Spain, EST = Estonia, ETH = Ethiopia, FIN = Finland, FRA = France, FSM = Micronesia, GAB = Gabon, GBR = United Kingdom, GEO = Georgia, GIN = Guinea, GNB = Guinea-Bissau, GRC = Greece, GTM = Guatemala GUY = Guyana, HUN = Hungary, HTI = Haiti, IDN = Indonesia, IND = India, IRL = Ireland, IRN = Iran, ISL = Iceland, ISR = Israel, ITA = Italy, JAM = Jamaica, JOR = Jordan, JPN = Japan, KAZ = Kazakhstan, KGZ = Kyrgyzstan, KEN = Kenya, KOR = Korea, LAO = Laos, LBR = Liberia, LCA = Saint Lucia, LKA = Sri Lanka, LSO = Lesotho, MAR = Morocco, MDG = Madagascar, MDV = Maldives, MEX = Mexico, MHL = Marshall Islands, MLI = Mali, MMR = Myanmar, MNE = Montenegro, MNG = Mongolia, MOZ = Mozambique, MRT = Mauritania, MUS = Mauritius, MWI = Malawi, MYS = Malaysia, NAM = Namibia, NER = Niger, NGA = Nigeria, NIC = Nicaragua, NOR = Norway, NPL = Nepal, PAK = Pakistan, PAN = Panama, PER = Peru, PHL = Phillipines, PNG = Papua New Guinea, PRT = Portugal, PRY = Paraguay, ROU = Romania, RUS = Russia, RWA = Rwanda, SDN = Sudan, SEN = Senegal, SLB = Solomon Islands, SLE = Sierra Leone, SLV = El Salvador, SSD = South Sudan, STP = Sao Tome and Principe, SUR = Suriname, SWE = Sweden, SWZ = Eswatini, SYC = Seychelles, SYR = Syria, TCD = Chad, THA = Thailand, TKM = Turkmenistan, TTO = Trinidad and Tobago, TUR = Türkiye, TZA = Tanzania, UGA = Uganda, UKR = Ukraine, URY = Uruguay, USA = United States, UZB = Uzbekistan, VEN = Venezuela, VNM = Vietnam, YEM = Yemen, ZAF = South Africa, ZMB = Zambia, ZWE = Zimbabwe

Averaging the residuals of the relationship shown in Fig. 6 by region indicates which regions will have the highest burden of child mortality after poverty and population size are taken into account (Fig. 8). This summary analysis indicates that sub-Saharan Africa is still the region with the greatest burden of child mortality. Latin America/Caribbean is a region with an approximately expected burden of child mortality, whereas other high-income nations and Europe/Central Asia will have fewer child deaths than otherwise expected (Fig. 8).

Figure 8. Mean residuals (across countries) of the relationship between population size-standardised child deaths predicted from 2022 to 2100 and national poverty (see Fig. 6) by major global region. Blue (mean negative residual) bars indicate the regions with lower-than-predicted child deaths, and red bars (mean positive residual) indicate regions with higher-than-predicted child deaths.



Assessing the effects of overpopulation on future children

To determine the risks for future children and provide the opportunity to counter serious threats, accurate information on the outlook for their health and wellbeing is essential. For assessing risk, infant mortality is an important index of a society's ability to protect children's health. To produce projections of infant mortality from 2022 to 2100, the United Nations used their own *Medium* fertility variant for population growth (22) and fitted a smoothed line to previous data on infant mortality for each country, and then extrapolated this to 2100 (8). This methodology assumes a business-as-usual expectation that the pattern of decreasing infant mortality over the last few decades will continue unchanged into the future. It relies on retrospective mortality data and does not consider the increasing risks to infants as population rises and the expectation of increasing risks to children as climate change worsens (2, 44, 117). Hence, the United Nations' approach will inevitably underestimate the number of children who will die this century.

Although United Nations' data on infant mortality rates show a continuing decline to 2021 under the *Medium* projection variation (169), the time when improvements to health are reversed by climate change and overpopulation might have already arrived, given recent evidence suggesting that infant mortality is already increasing in countries from several different regions. For example, recent increases have been observed in both the USA and France (170, 171), as well as in India, Madagascar, Cambodia, Nepal, and the Philippines (172).

Access to quality family planning benefits children's health

A proven approach to reducing fertility is to give all men and women access to free, voluntary, culturally sensitive, locally appropriate, quality family-planning services. Such access allows prospective parents to choose the size of their family and is considered a human right (16). Even though this is part of the United Nations' Sustainable Development Goal 3.7 (173) and has been supported by the World Health Organization (16, 174), the unmet need has received less attention than climate change. According to a World Bank report, the intervention of meeting 90% of the unmet need for contraception alone in 2015 would have reduced annual global births by 28 million and averted 440,000 neonatal and 473,000 child deaths (175). Because countries with unmet contraception needs (176) are those with the highest fertility rates and the highest population growth (177), these numbers will increase over coming decades. With the likely decline in health as continuing rapid population growth in these countries outstrips resource availability, the true increase in neonatal and child deaths will be much greater. Reduced fertility will therefore help to protect future children from early death or a life of ill health.

Several factors beyond access to quality family planning are associated with lower fertility rates. These include higher maternal education (178), lower infant mortality (46), greater socio-economic prosperity (179), and lower religious adherence (180). Although these associations have often been interpreted as causal (178, 181), there are many potential confounding interactions. For example, women who are more educated are likely to be more prosperous than those who less-educated, and the relationship between high infant mortality and high fertility can be bi-directional in causality, because high infant mortality can increase fertility, whereas higher fertility can increase infant mortality (182-184). The evidence that fertility declines as soon as quality family planning is available is extensive, with poignant examples from Bangladesh (185-187), Kenya (189), and Iran (189, 190). At the country scale, lower fertility is related to lower infant mortality, lower household size, and increased access to contraception, each of these being more important than either female education or religious adherence (46). In short, efforts to increase access to family planning will counter the self-facilitation feedback of increasing population on increasing infant and child mortality in low- and middle-income countries.

There have been no modelled projections of the effects of various scenarios for increasing the availability of family planning in countries with unmet needs of contraception on childhood deaths, while simultaneously considering resource and nutrition limitation and climate change. Demonstrating the importance of this issue to the health of future children would provide compelling evidence for a much greater focus on implementing the introduction of high-quality family planning across the globe to reduce deaths and suffering in future generations of children.

Future prospects for children

We have provided the first summary of the evidence that overpopulation is adversely affecting children and that further increases in population will have increasingly serious consequences for children in the future unless substantial measures are taken to reverse population growth. Our analyses emphasise that most children born this century will be in sub-Saharan Africa and Central/South Asia where malnutrition is already high, the capacity to increase crop yields is low, and the impacts of climate change on child health are high and already contributing to infant mortality. Low-income nations have the fewest resources to protect higher numbers of children from the effects of overpopulation and the deteriorating climate. We also emphasise that the need to reduce population to protect future children must include wealthy, high-consumption nations. A global reduction in population is essential if the future of prosperous and healthy human societies on this planet is to be secured. If we want to be responsible global custodians, respecting the rights of current and future children to a healthy life is essential. Transferring this message broadly could reduce unnecessary deaths in infants and children and assist in mitigating environmental damage. More discussion of future child health would also assist in finding ethical means to bend down the trend in global population. The need for high-quality and wide-ranging research to determine what is needed to provide a healthy environment for future children is one of the greatest unmet needs for global health research.

References

1. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Belesova K, Boykoff M, et al. 2019. The 2019 report of *The Lancet Countdown* on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *Lancet* 394:1836-1878
2. IPCC. 2022. Summary for Policymakers. Pörtner H-O, Roberts DC, Poloczanska ES, Mintenbeck K, Tignor M, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A (eds). In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Tignor M, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds). Cambridge University Press, Cambridge, UK and New York, USA, pp. 3-33, doi:10.1017/9781009325844.001
3. WHO. 2021. Climate Change and Health. World Health Organization, Geneva
4. Weeda LJZ, Bradshaw CJA, Judge MA, Saraswati CM, Le Souëf PN. 2024. How climate change degrades child health: a systematic review and meta-analysis. *Science of The Total Environment* 920:170944
5. Crist E, Ripple WJ, Ehrlich PR, Rees WE, Wolf C. 2022. Scientists' warning on population. *Science of the Total Environment* 845:157166
6. Kopnina H, Washington H. 2016. Discussing why population growth is still ignored or denied. *Chinese Journal of Population Resources and Environment* 14:133-43
7. Ehrlich PR. 2021. Why no mention of overpopulation in talk of food systems? *Nature* 598:257
8. United Nations. 2022. World Population Prospects: Infant Mortality Rate, for Both Sexes Combined (Infant Deaths per 1,000 Live Births). United Nations Population Division, Geneva. data.un.org/Data.aspx?d=PopDiv&f=variableID%3A77
9. Ahdoot S, Pacheco SE. 2015 Global climate change and children's health. *Pediatrics* 136:e1468-84
10. Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, et al. 2018. Net-zero emissions energy systems. *Science* 360:eaas9793
11. United Nations Climate Change. 2022. *Summary of Global Climate Action at COP 27*. Global Climate Action, United Nations Climate Change, Geneva. unfccc.int/sites/default/files/resource/GCA_COP27_Summary_of_Global_Climate_Action_at_COP_27_1711.pdf
12. Convention on Biological Diversity. 2022. COP15: Nations Adopt Four goals, 23 Targets for 2030 in Landmark UN Biodiversity Agreement. 19 November 2022. cbd.int/article/cop15-cbd-press-release-final-19dec2022
13. United Nations. 2022. *The Sustainable Development Goals Report 2022*. United Nations, Department of Economic and Social Affairs, New York. unstats.un.org/sdgs/report/2022
14. Bradshaw CJA, Strona G. 2022. Children born today will see literally thousands of animals disappear in their lifetime, as global food webs collapse. *The Conversation*. theconversation.com/children-born-today-will-see-literally-thousands-of-animals-disappear-in-their-lifetime-as-global-food-webs-collapse-196286
15. Bradshaw CJA, Ehrlich PR, Beattie A, Ceballos G, Crist E, Diamond J, et al. 2021. Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science* 1:615419
16. World Health Organization. 2015. *Ensuring Human Rights Within Contraceptive Service Delivery: Implementation Guide*. World Health Organization & United Nations Population Fund, Geneva. who.int/publications/i/item/9789241549103
17. Prata N, Fraser A, Huchko MJ, Gipson JD, Withers M, Lewis S, et al. 2017. Women's empowerment and family planning: a review of the literature. *Journal of Biosocial Science* 49:713-743
18. Klein Goldewijk K, Beusen A, van Drecht G, de Vos M. 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography* 20:73-86
19. United Nations. 2019. *World Population Prospects 2019* (aggregates). United Nations, Department of Economic

and Social Affairs, Population Division, Geneva. population.un.org/wpp
20. Roser M, Ritchie H, Ortiz-Ospina E, Rodes-Guirao L. 2019. *World Population Growth*. Our World in Data. ourworldindata.org
21. United Nations. 2022. 9.7 Billion on Earth by 2050, But Growth Rate Slowing, Says New UN Population Report. Geneva. un.org/en/academic-impact/97-billion-earth-2050-growth-rate-slowing-says-new-un-population-report#:~:text=Between%20now%20and%202050%2C%20that,at%20least%2010%20per%20cent
22. United Nations. 2022. *World Population Prospects*. United Nations, Department of Economic and Social Affairs, Population Division. 2022. population.un.org/wpp
23. Rees WE. 2023. The human eco-predicament: overshoot and the population conundrum. *Vienna Yearbook of Population Research* 21:1-19
24. UNICEF. 2023. *Prospects for Children in the Polycrisis: A 2023 Global Outlook*. United Nations Children's Fund, New York. unicef.org/innocenti/reports/prospects-children-polycrisis-2023-global-outlook
25. Pronczuk J, Surdu S. 2008. Children's environmental health in the twenty-first century. *Annals of the New York Academy of Sciences* 1140:143-154
26. Rees WE. 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* 4:121-130
27. Global Footprint Network. 2022. *Ecological Footprint of Countries 2022*. data.footprintnetwork.org
28. Saraswati CM, Judge MA, Weeda LJZ, Bassat Q, Prata N, Le Souëf PN, Bradshaw CJA. 2024. Net benefit of smaller human populations to environmental integrity and individual health and wellbeing. *Frontiers in Public Health* 12:1339933
29. Barnard P, Moomaw WR, Fioramonti L, Laurance WF, Mahmoud MI, O'Sullivan J, et al. 2021. World scientists' warnings into action, local to global. *Science Progress*. 104. doi:10.1177/00368504211056290
30. IPCC. 2021. Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds). Cambridge University Press, Cambridge, United Kingdom and New York, USA, pp. 3−32, doi:10.1017/9781009157896.001.
31. Seibert MK, Rees WE. 2021. Through the eye of a needle: an eco-heterodox perspective on the renewable energy transition. *Energies*. 14:4508
32. Encyclopaedia Britannica. 2022. *Overpopulation*. britannica.com/science/overpopulation
33. Kerem N. 2022. *The Pursuit of Rights and Choices for All*. 3 November 2022. un.org/en/un-chronicle/pursuit-rights-and-choices-all-0
34. Pirani S. 2021. The populationists' ghastly future. *The Ecologist* theecologist.org/2021/may/28/populationists-ghastly-future
35. Bookchin M. 2022. *The Population Myth*. 3 November 2022. *The Anarchist Library* theanarchistlibrary.org/library/murray-bookchin-the-population-myth
36. Piper K. 2019. We've worried about overpopulation for centuries. And we've always been wrong. *Vox* vox.com/future-perfect/2019/8/20/20802413/overpopulation-demographic-transition-population-explained
37. Bluwstein J, Asiyanbi AP, Dutta A, Huff A, Lund JF, Rosa SPD, Steinberger J. 2021. Commentary: Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science* 1:615419
38. Maynard R. 2021. Overpopulation denial syndrome. *Ecological Citizen* 5:epub-044
39. Strona G, Bradshaw CJA. 2022. Coextinctions dominate future vertebrate losses from climate and land use change. *Science Advances* 8:eabn4345
40. Rees, WE. 2017. The human ecological predicament: wages of self-delusion. Millennium Alliance for Humanity and the Biosphere, Stanford University, Stanford. mahb.stanford.edu/blog/human-eco-predicament
41. Washington H, Lowe I, Kopnina H. 2020. Why do society and academia ignore the 'Scientists Warning to Humanity' on population? *Journal of Futures Studies* 25:93-106
42. Rees WE. 2023. Overshoot: cognitive obsolescence and the population conundrum. *Population and Sustainability* 7:15-38
43. Saeed S, Makhdum MSA, Anwar S, Yaseen MR. 2023. Climate change vulnerability, adaptation, and feedback hypothesis: a comparison of lower-middle, upper-middle, and high-income countries. *Sustainability* 15:4145
44. IPCC. 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth

Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Lee H, Romero J (eds). IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647
45. Guerra S, Roope LS, Tsiachristas A. 2024. Assessing the relationship between coverage of essential health services and poverty levels in low- and middle- income countries. *Health Policy and Planning* 39:156-167
46. Bradshaw CJA, Perry C, Saraswati CM, Judge M, Heyworth J, Le Souëf PN. Lower infant mortality, lower household size, and more access to contraception reduce fertility in low- and middle-income nations. *PLoS One* 18:e0280260
47. Hickel J, O'Neill DW, Fanning AL, Zoomkawala H. 2022. National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970-2017. *The Lancet Planetary Health* 6:e342-e349
48. Bradshaw CJA, Judge MA, Blumstein D, Ehrlich P, Dasgupta A, Wackernagel M, Weeda LJZ, Le Souëf PN. 2024. Global human population ended self-facilitation in the 1950s. *SSRN* doi:10.2139/ssrn.4788003
49. Ehrlich PR, Holdren JP. 1971. Impact of population growth. *Science* 171:1212-1217
50. Owusu P, Asumadu-Sarkodie S. 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering* 3:1157990
51. Rees WE, Wackernagel M. 2013. The shoe fits, but the footprint is larger than Earth. *PLoS Biology* 11:e1001701
52. Commonweath Scientific and Industrial Research Organisation. 2023. *Cape Grim Greenhouse Gas Data*. 29 January 2024. capegrim.csiro.au
53. Commonweath Scientific and Industrial Research Organisation. 2022. *Latest Cape Grim Greenhouse Gas Data*. 10 November 2022. csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data
54. International Energy Agency. 2022. Global Energy Review: CO_2 Emissions in 2021. Global Emissions Rebound Sharply to Highest Ever Level. International Energy Agency. iea.org/reports/global-energy-review-co2-emissions-in-2021-2
55. Sorrell S. 2009. Jevons' paradox revisited: the evidence for backfire from improved energy efficiency. *Energy Policy* 37:1456-1469
56. Sharrow D, Hug L, You D, Alkema L, Black R, Cousens S, et al. 2022. Global, regional, and national trends in under-5 mortality between 1990 and 2019 with scenario-based projections until 2030: a systematic analysis by the UN Inter-agency Group for Child Mortality Estimation. *The Lancet Global Health* 10:e195-e206
57. Heft-Neal S, Burney J, Bendavid E, Burke M. 2018. Robust relationship between air quality and infant mortality in Africa. *Nature* 559:254-258
58. Burke M, Heft-Neal S, Bendavid E. Sources of variation in under-5 mortality across sub-Saharan Africa: a spatial analysis. *The Lancet Global Health* 4:e936-e945
59. Das Gupta M. 2013. *Population, Poverty, and Climate Change*. World Bank. Washington, DC
60. Bradshaw CJA, Otto SP, Annamalay AA, Heft-Neal S, Wagner Z, et al. 2019. Testing the socioeconomic and environmental determinants of better child-health outcomes in Africa: a cross-sectional study among nations. *BMJ Open* 9:e029968
61. Cortes-Ramirez J, Wilches-Vega JD, Paris-Pineda OM, Rod JE, Ayurzana L, Sly PD. 2021. Environmental risk factors associated with respiratory diseases in children with socioeconomic disadvantage. *Heliyon* 7:e06820
62. Aaby P, Bukh J, Lisse IM, Smits AJ. 1983. Spacing, crowding, and child mortality in Guinea-Bissau. *The Lancet* 2:161
63. Unwin N, Alberti K. 2006. Chronic non-communicable diseases. *Annals of Tropical Medicine and Parasitology* 100:455-464
64. Eckert S, Kohler S. 2014. Urbanization and health in developing countries: a systematic review. *World Health and Population* 15:7-20
65. Craig J, Haskey J. 1978. The relationships between the population, area, and density of urban areas. *Urban Studies* 15:101-107
66. Borck R, Schrauth P. 2021. Population density and urban air quality. *Regional Science and Urban Economics* 86:103596
67. Health Effects Institute. 2022. *The State of Air Quality and Health Impacts in Africa*. State of Global Air Initiative and Institute for Health Metrics and Evaluation, Boston. healthdata.org/research-analysis/library/state-air-quality-and-health-impacts-africa
68. Kaur R, Pandey P. 2021. Air pollution, climate change, and human health in Indian cities: a brief review. *Frontiers in Sustainable Cities* 3:705131

69. Brumberg HL, Karr CJ, Bole A, Ahdoot S, Balk SJ, Bernstein AS, Byron LG, Landrigan PJ, Marcus SM, Nerlinger AL, et al. 2021. Ambient air pollution: health hazards to children. *Pediatrics* 147:e2021051484
70. Chipeta MG, Kumaran EPA, Browne AJ, Hamadani BHK, Haines-Woodhouse G, Sartorius B, et al. 2022. Mapping local variation in household overcrowding across Africa from 2000 to 2018: a modelling study. *The Lancet Planetary Health* 6:e670-e681
71. Reiner RC, Jr., Smith DL, Gething PW. 2015. Climate change, urbanization and disease: summer in the city … *Transactions of the Royal Society of Tropical Medicine and Hygiene* 109:171-172
72. Hathi P, Haque S, Pant L, Coffey D, Spears D. 2017. Place and child health: the interaction of population density and sanitation in developing countries. *Demography* 54:337-360
73. Kabaria CW, Gilbert M, Noor AM, Snow RW, Linard C. 2017. The impact of urbanization and population density on childhood *Plasmodium falciparum* parasite prevalence rates in Africa. *Malaria Journal* 16:1-10
74. Gustafson P, Gomes VF, Vieira CS, Rabna P, Seng R, Johansson P, et al. 2004. Tuberculosis in Bissau: incidence and risk factors in an urban community in sub-Saharan Africa. *International Journal of Epidemiology* 33:163-172
75. Kraemer R. 1993. Whole-body plethysmography in the clinical assessment of infants with bronchopulmonary diseases. *Respiration* 60:1-8
76. Levy B. 2018. Exploratory investigation of region level risk factors of Ebola virus disease in West Africa. *PeerJ* 6:e5888
77. Buvé A, Bishikwabo-Nsarhaza K, Mutangadura G. 2002. The spread and effect of HIV-1 infection in sub-Saharan Africa. *The Lancet* 359(9322):2011-2017
78. Asadgol Z, Badirzadeh A, Niazi S, Mokhayeri Y, Kermani M, Mohammadi H, et al. 2020. How climate change can affect cholera incidence and prevalence? A systematic review. *Environmental Science and Pollution Research* 27:34906-34926
79. Connolly C, Ali SH, Keil R. 2020. On the relationships between COVID-19 and extended urbanization. *Dialogues in Human Geography* 10:213-216
80. Ye T, Guo Y, Abramson MJ, Li T, Li S. 2023. Greenspace and children's lung function in China: a cross-sectional study between 2013 and 2015. *Science of the Total Environment* 858:159952
81. McCormick R. 2017. Does access to green space impact the mental well-being of children: a systematic review. *Journal of Pediatric Nursing* 37:3-7
82. Speldewinde PC, Cook A, Davies P, Weinstein P. 2009. A relationship between environmental degradation and mental health in rural Western Australia. *Health and Place* 15:865-872
83. Kloog I. 2019. Air pollution, ambient temperature, green space and preterm birth. *Current Opinion in Pediatrics* 31:237-243
84. Mueller W, Milner J, Loh M, Vardoulakis S, Wilkinson P. 2022. Exposure to urban greenspace and pathways to respiratory health: an exploratory systematic review. *Science of the Total Environment* 829:154447
85. Bradshaw CJ, Brook BW. 2016. Implications of Australia's population policy for future greenhouse gas emissions targets. *Asia and Pacific Policy Studies* 3:249-265
86. Australian Bureau of Statistics. 2023. *National, State and Territory Population*. Canberra. abs.gov.au/statistics/people/population/national-state-and-territory-population/latest-release
87. Borg R. 2023. It's a life cycle. Experts weigh in as Australia prepares to welcome 900k people to the country. news.com.au/lifestyle/real-life/news-life/its-a-life-cycle-experts-weigh-in-as-australia-prepares-to-welcome-900k-people-to-the-country/news-story/72947f621d10b17ce00e36a57d3fb6de
88. Australian Institute of Health and Welfare. 2012. Australia's Food and Nutrition 2012: In Brief. Australian Institute of Health and Welfare, Canberra. aihw.gov.au/reports/food-nutrition/australias-food-nutrition-2012-in-brief/summary
89. Orians GH, Milewski AV. 2007. Ecology of Australia: the effects of nutrient-poor soils and intense fires. *Biological Reviews* 82:393-423
90. Eldridge DJ, Maestre FT, Koen TB, Delgado-Baquerizo M. 2018. Australian dryland soils are acidic and nutrient-depleted, and have unique microbial communities compared with other drylands. *Journal of Biogeography* 45:2803-2814
91. Australian Security Leaders Climate Group. 2022. *Food Fight: Climate change, Food Crises and Regional Insecurity*. Australian Security Leaders Climate Group. Manuka, Australian Capital Territory. mysecuritymarketplace.com/reports/food-fight-climate-change-food-crises-regional-insecurity

92. Linehan V, Thorpe S, Andrews N, Kim Y, Beaini F. 2012. Food demand to 2050, Opportunities for Australian agriculture. 42nd ABARES Outlook conference 6–7 March 2012; Australian Bureau of Agricultural and Resource Economics and Sciences Canberra
93. Mbow C, Rosenzweig C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, Liwenga E, Pradhan P, Rivera-Ferre MG, Sapkota T, Tubiello FN, Xu Y. 2019: *Food Security*. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J. doi:10.1017/9781009157988.007
94. Boone RB, Conant RT, Sircely J, Thornton PK, Herrero M. 2018. Climate change impacts on selected global rangeland ecosystem services. *Global Change Biology* 24:1382-1393.
95. Australian Bureau of Agricultural and Resource Economics and Sciences. 2023. *Snapshot of Australian Agriculture 2023*. Australian Government Department of Agriculture, Fisheries and Forestry, Canberra. agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture
96. Alexandratos N, Bruinsma J. 2012. *World Agriculture Towards 2030/2050: the 2012 Revision*. ESA Working paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome. doi:10.22004/ag.econ.288998
97. van Dijk M, Morley T, Rau M, Saghai Y. 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food* 2: 494-501.
98. Myers SS, Smith MR, Guth S, Golden CD, Vaitla B, Mueller ND, et al. 2017. Climate change and global food systems: potential impacts on food security and undernutrition. *Annual Review of Public Health* 38:259-277
99. United Nations Children's Fund, World Health Organization, International Bank for Reconstruction and Development/The World Bank. 2020. *Levels and Trends in Child Malnutrition: Key Findings of the 2020 Edition of the Joint Child Malnutrition Estimates.* World Health Organization, Geneva. who.int/publications/i/item/9789240003576
100. IPCC. 2019: *Summary for Policymakers*. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds). doi:10.1017/9781009157988.001
101. Food and Agricultural Organization of the United Nations. 2016. *Climate Change and Food Security: Risks and Responses*. Food and Agriculture Organization of the United Nations, Rome. openknowledge.fao.org/handle/20.500.14283/i5188e
102. Owolade AJ-J, Abdullateef RO, Adesola RO, Olaloye ED. 2022. Malnutrition: an underlying health condition faced in sub Saharan Africa: challenges and recommendations. *Annals of Medicine and Surgery* 82:104769
103. Borlaug N. 2007. Feeding a hungry world. *Science* 318:359
104. FAO, IFAD, UNICEF, WFP and WHO. 2022. *The State of Food Security and Nutrition in the World 2022*. Repurposing food and agricultural policies to make healthy diets more affordable. Food and Agriculture Organization of the United Nations, Rome. doi:10.4060/cc0639en
105. Whitton C, Bogueva D, Marinova D, Phillips CJC. 2021. Are we approaching peak meat consumption? Analysis of meat consumption from 2000 to 2019 in 35 countries and its relationship to gross domestic product. *Animals* 11:3466
106. Rice AL, Sacco L, Hyder A, Black RE. 2000. Malnutrition as an underlying cause of childhood deaths associated with infectious diseases in developing countries. Bulletin of the World Health Organization 78:1207-1221
107. Bassat Q, Blau DM, Ogbuanu IU, Samura S, Kaluma E, Bassey IA, et al. 2023. Causes of death among infants and children in the Child Health and Mortality Prevention Surveillance (CHAMPS) network. *JAMA Network Open* 6:e2322494
108. Amir-Ud-Din R, Naz L, Rubi A, Usman M, Ghimire U. 2021. Impact of high-risk fertility behaviours on under five mortality in Asia and Africa: evidence from Demographic and Health Surveys. *BMC Pregnancy and Childbirth* 21:344
109. Bjornlund V, Bjornlund H, Van Rooyen A. 2020. Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world – a historical perspective. *International Journal of Water Resources Development* 36:S20-S53

110. Bradshaw CJA, Di Minin E. 2019. Socio-economic predictors of environmental performance among African nations. *Scientific Reports* 9:9306
111. United Nations Children's Fund. 2023. *WHO, World Bank Group Joint Malnutrition Estimates, May 2023 Edition. Global Prevalence and Numbers Affected 2000-2022*. United Nations Children's Fund, New York. data.unicef.org/resources/dataset/malnutrition-data
112. World Health Organization. 2023. WHO Fact sheets — malnutrition. 20 December 2023. who.int/news-room/fact-sheets/detail/malnutrition
113. Black RE, Victora CG, Walker SP, Bhutta ZA, Christian P, de Onis M, et al. 2015. Maternal and child undernutrition and overweight in low-income and middle-income countries. *The Lancet* 382:427-451.
114. O'Lenick CR, Winquist A, Chang HH, Kramer MR, Mulholland JA, Grundstein A, et al. 2017. Evaluation of individual and area-level factors as modifiers of the association between warm-season temperature and pediatric asthma morbidity in Atlanta, GA. *Environmental Research* 156:132-144
115. Soneja S, Jiang C, Fisher J, Upperman CR, Mitchell C, Sapkota A. 2016. Exposure to extreme heat and precipitation events associated with increased risk of hospitalization for asthma in Maryland, U.S.A. *Environmental Health* 15:57
116. Thompson AA, Matamale L, Kharidza SD. 2012. Impact of climate change on children's health in Limpopo Province, South Africa. *International Journal of Environmental Research and Public Health* 9:831-854
117. IPCC. 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/9781009157896
118. PubMed. 2022. Search: "climate change child health". pubmed.ncbi.nlm.nih.gov/?term=climate%20change%20child%20health&sort=pubdate&timeline=expanded
119. Uibel D, Sharma R, Piontkowski D, Sheffield PE, Clougherty JE. 2022. Association of ambient extreme heat with pediatric morbidity: a scoping review. *International Journal of Biometeorology* 66:1683-1698
120. Chersich MF, Pham MD, Areal A, Haghighi MM, Manyuchi A, Swift CP, et al. 2020. Associations between high temperatures in pregnancy and risk of preterm birth, low birth weight, and stillbirths: systematic review and meta-analysis. *BMJ* 371:m3811
121. Gat R, Kachko E, Kloog I, Erez O, Yitshak-Sade M, Novack V, et al. Differences in environmental factors contributing to preterm labor and PPROM - Population based study. Environmental research. 2021;196:110894.
122. Huang M, Strickland MJ, Richards M, Holmes HA, Newman AJ, Garn JV, et al. 2021. Acute associations between heatwaves and preterm and early-term birth in 50 US metropolitan areas: a matched case-control study. *Environmental Health* 20:47
123. Xu Z, Etzel RA, Su H, Huang C, Guo Y, Tong S. 2012. Impact of ambient temperature on children's health: a systematic review. *Environmental Research* 117:120-131
124. Álvaro-Meca A, Goez MDC, Resino R, Matías V, Sepúlveda-Crespo D, Martínez I, et al. 2022. Environmental factors linked to hospital admissions in young children due to acute viral lower respiratory infections: a bidirectional case-crossover study. *Environmental Research* 212:113319
125. Figgs LW. 2019. Emergency department asthma diagnosis risk associated with the 2012 heat wave and drought in Douglas County NE, USA. *Heart and Lung* 48:250-257
126. Winquist A, Grundstein A, Chang HH, Hess J, Sarnat SE. 2016. Warm season temperatures and emergency department visits in Atlanta, Georgia. *Environmental Research* 147:314-323
127. Xu Z, Hu X, Tong S, Cheng J. 2020. Heat and risk of acute kidney injury: an hourly-level case-crossover study in Queensland, Australia. *Environmental Research* 182:109058
128. Johnson RJ, Sánchez-Lozada LG, Newman LS, Lanaspa MA, Diaz HF, Lemery J, et al. 2019. Climate Change and the kidney. *Annals of Nutrition and Metabolism* 74:38-44
129. Al-Shihabi F, Moore A, Chowdhury TA. 2022. Diabetes and climate change. *Diabetic Medicine* 40:e14971
130. Bogar K, Brensinger CM, Hennessy S, Flory JH, Bell ML, Shi C, et al. 2022. Climate change and ambient temperature extremes: association with serious hypoglycemia, diabetic ketoacidosis, and sudden cardiac arrest/ventricular arrhythmia in people with type 2 diabetes. *Diabetes Care* 45:e171–e173
131. Zilbermint M. Diabetes and climate change. J Community Hosp Intern Med Perspect. 2020;10(5):409-12.

132. Cuschieri S, Calleja Agius J. 2021. The interaction between diabetes and climate change — a review on the dual global phenomena. *Early Human Development* 155:105220
133. Emont JP, Ko AI, Homasi-Paelate A, Ituaso-Conway N, Nilles EJ. 2017. Epidemiological investigation of a diarrhea outbreak in the South Pacific island nation of Tuvalu during a severe La Niña-associated drought emergency in 2011. *American Journal of Tropical Medicine and Hygiene* 96:576-582
134. Milani GP, Lo Leggio A, Castellazzi ML, Agostoni C, Bianchetti MG, Carugno M. 2022. Outdoor temperature and circulating sodium in children with acute gastroenteritis. *Pediatric Research* 92:1270-1273
135. Shah MM, Krystosik AR, Ndenga BA, Mutuku FM, Caldwell JM, Otuka V, et al. 2019. Malaria smear positivity among Kenyan children peaks at intermediate temperatures as predicted by ecological models. *Parasites and Vectors* 12:288
136. Wilk P, Gunz A, Maltby A, Ravichakaravarthy T, Clemens KK, Lavigne É, et al. 2021. Extreme heat and paediatric emergency department visits in Southwestern Ontario. *Paediatrics and Child Health* 26:305-309
137. Xu Z, FitzGerald G, Guo Y, Jalaludin B, Tong S. 2019 Assessing heatwave impacts on cause-specific emergency department visits in urban and rural communities of Queensland, Australia. *Environmental Research* 168:414-419
138. Patel D, Jian L, Xiao J, Jansz J, Yun G, Robertson A. 2019. Joint effect of heatwaves and air quality on emergency department attendances for vulnerable population in Perth, Western Australia, 2006 to 2015. *Environmental Research* 174:80-87
139. Nitschke M, Tucker GR, Hansen AL, Williams S, Zhang Y, Bi P. 2011. Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environmental Health* 10:42
140. Fisher JD, Shah AP, Norozian F. 2022. Clinical spectrum of pediatric heat illness and heatstroke in a North American desert climate. *Pediatric Emergency Care* 38:e891-e893
141. Ma T, Moore J, Cleary A. 2022. Climate change impacts on the mental health and wellbeing of young people: a scoping review of risk and protective factors. *Social Science and Medicine* 301:114888
142. Wyrwoll CS, Papini MG, Chivers EK, Yuan J, Pavlos NJ, Lucas RM, et al. 2022. Long-term exposure of mice to 890 ppm atmospheric CO_2 alters growth trajectories and elicits hyperactive behaviours in young adulthood. *Journal of Physiology* 600:1439-1453
143. Larcombe AN, Papini MG, Chivers EK, Berry LJ, Lucas RM, Wyrwoll CS. 2021. Mouse lung structure and function after long-term exposure to an atmospheric carbon dioxide level predicted by climate change modeling. *Environmental Health Perspectives* 129:17001
144. McElroy S, Ilango S, Dimitrova A, Gershunov A, Benmarhnia T. 2022. Extreme heat, preterm birth, and stillbirth: a global analysis across 14 lower-middle income countries. *Environment International* 158:106902
145. Jegasothy E, Randall DA, Ford JB, Nippita TA, Morgan GG. 2022. Maternal factors and risk of spontaneous preterm birth due to high ambient temperatures in New South Wales, Australia. *Paediatric and Perinatal Epidemiology* 36:4-12
146. Undela K, Mohammed BTS, Gurumurthy P, Doreswamy SM. 2019. Impact of preterm birth and low birth weight on medical conditions, medication use and mortality among neonates: a prospective observational cohort study. *World Journal of Pediatrics* 15:281–288
147. Samuels L, Nakstad B, Roos N, Bonell A, Chersich M, Havenith G, et al. 2022. Physiological mechanisms of the impact of heat during pregnancy and the clinical implications: review of the evidence from an expert group meeting. *International Journal of Biometeorology* 66:1505-1513
148. Gao J, Sun Y, Lu Y, Li L. 2014. Impact of ambient humidity on child health: a systematic review. *PLoS One* 9:e112508
149. Chatkin J, Correa L, Santos U. 2021. External environmental pollution as a risk factor for asthma. *Clinical Reviews in Allergy and Immunology* 12:1-18
150. To T, Zhu J, Stieb D, Gray N, Fong I, Pinault L, et al. 2020. Early life exposure to air pollution and incidence of childhood asthma, allergic rhinitis and eczema. *European Respiratory Journal* 55:1900913
151. Xu Z, Huang C, Hu W, Turner LR, Su H, Tong S. 2013. Extreme temperatures and emergency department admissions for childhood asthma in Brisbane, Australia. *Occupational and Environmental Medicine* 70:730-735
152. O'Lenick CR, Winquist A, Chang HH, Kramer MR, Mulholland JA, Grundstein A, et al. 2017. Evaluation of individual and area-level factors as modifiers of the association between warm-season temperature and pediatric asthma morbidity in Atlanta, GA. *Environmental Research* 156:132-144
153. Xu R, Zhao Q, Coelho M, Saldiva PHN, Abramson MJ, Li S, et al. 2020. Socioeconomic level and associations

between heat exposure and all-cause and cause-specific hospitalization in 1,814 Brazilian cities: a nationwide case-crossover study. *PLoS Medicine* 17:e1003369

154. Zhao Q, Li S, Coelho M, Saldiva PHN, Hu K, Arblaster JM, et al. 2019. Geographic, demographic, and temporal variations in the association between heat exposure and hospitalization in Brazil: a nationwide study between 2000 and 2015. *Environmental Health Perspectives* 127:17001
155. United Nations Children's Fund. 2016. *Uprooted. The Growing Crisis for Refugee and Migrant Children*. United Nations Children's Fund, New York. data.unicef.org/resources/uprooted-growing-crisis-refugee-migrant-children
156. Williams PC, Marais B, Isaacs D, Preisz A. 2021. Ethical considerations regarding the effects of climate change and planetary health on children. *Journal of Paediatrics and Child Health* 57:1775-1780
157. Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, et al. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the USA* 114:9326-9331
158. Randell H, Gray C, Grace K. 2020. Stunted from the start: early life weather conditions and child undernutrition in Ethiopia. *Social Science and Medicine*. 261:113234
159. United Nations Children's Fund. 2021. *The Climate Crisis is a Child Rights Crisis. Introducing the Children's Climate Risk Index*. United Nations Children's Fund, New York. unicef.org/reports/climate-crisis-child-rights-crisis
160. Edmonds HK, Lovell JE, Lovell CAK. 2020. A new composite climate change vulnerability index. *Ecological Indicators* 117:106529
161. World Bank. 2022. *The World by Income and Region*. datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html
162. United Nations Children's Fund. 2024. *The State of the World's Children 2023: Statistical Tables*. 4 January 2024. United Nations Children's Fund, New York. data.unicef.org/resources/dataset/the-state-of-the-worlds-children-2023-statistical-tables
163. United Nations Population Division. 2023. *World Population Prospects: 2022 Revision*. Population ages 0-14, total. World Bank. 4 January 2024. data.worldbank.org/indicator/SP.POP.0014.TO
164. Hamadeh N, Van Rompaey C, Metreau E. 2023. World Bank Group country classifications by income level for FY24. *World Bank Blogs* worldbank.org/en/opendata/new-world-bank-group-country-classifications-income-level-fy24
165. Jahan S. 2008. Poverty and infant mortality in the Eastern Mediterranean region: a meta-analysis. *Journal of Epidemiology and Community Health* 62:745-751
166. Taylor-Robinson D, Lai ETC, Wickham S, Rose T, Norman P, Bambra C, et al. 2019. Assessing the impact of rising child poverty on the unprecedented rise in infant mortality in England, 2000-2017: time trend analysis. *BMJ Open* 9:e029424
167. Mohamoud YA, Kirby RS, Ehrenthal DB. County poverty, urban-rural classification, and the causes of term infant death: United States, 2012-2015. *Public Health Reports* 136:584-594
168. Sims M, Sims TL, Bruce MA. 2007. Urban poverty and infant mortality rate disparities. *Journal of the National Medical Association* 99:349-356
169. United Nations Department of Economic and Social Affairs. 2022. *World Population Prospects 2022: Summary of Results*. United Nations Department of Economic and Social Affairs, Population Division, Geneva. un.org/development/desa/pd/content/World-Population-Prospects-2022
170. Ely DM, Driscoll AK. 2024. Infant mortality in the United States, 2022: data from the period linked birth/infant death file *National Vital Statistics Reports* 73. doi:10.15620/cdc/157006
171. Trinh NTH, de Visme S, Cohen JF, Bruckner T, Lelong N, Adnot P, et al. 2022. Recent historic increase of infant mortality in France: a time-series analysis, 2001 to 2019. *The Lancet Reg Health – Europe* 16:100339
172. Wagner Z, Heft-Neal S, Wang Z, Jing R, Bendavid E. Infant and neonatal mortality during the COVID-19 pandemic: an interrupted time series analysis from five low- and middle-income countries. *medRχiv* doi:10.1101/2023.08.03.23293619
173. Nations U. The Sustainable Development Goals Report 2020. New York: United Nations Publications; 2020.
174. World Health Organization. 2014. *Ensuring Human Rights in the Provision of Contraceptive Information and Services: Guidance and Recommendations*. World Health Organization, Guidelines Review Committee, Sexual and Reproductive Health and Research, Geneva. who.int/publications/i/item/9789241506748
175. Black RE, Levin C, Walker N, Chou D, Liu L, Temmerman M. 2016. Reproductive, maternal, newborn, and child

health: key messages from Disease Control Priorities 3rd Edition. *The Lancet* 388:2811-2824
176. Wulifan JK, Brenner S, Jahn A, De Allegri M. 2016. A scoping review on determinants of unmet need for family planning among women of reproductive age in low and middle income countries. *BMC Women's Health* 16:2.
177. Bongaarts J. 2015. Global fertility and population trends. *Seminars in Reproductive Medicine* 33:5-10
178. Bongaarts J, Hardee K. 2019. Trends in contraceptive prevalence in sub-Saharan Africa: the roles of family planning programs and education. *African Journal of Reproductive Health* 23:96-105
179. Azmat SK, Ali M, Ishaque M, Mustafa G, Hameed W, Khan OF, et al. 2015. Assessing predictors of contraceptive use and demand for family planning services in underserved areas of Punjab province in Pakistan: results of a cross-sectional baseline survey. *Reproductive Health* 12:25
180. Turner N, Gotmark F. Human fertility and religions in sub-Saharan Africa: a comprehensive review of publications and data, 2010-2020. *African Journal of Reproductive Health* 27:119-171
181. Götmark F, Andersson M. 2020. Human fertility in relation to education, economy, religion, contraception, and family planning programs. *BMC Public Health* 20:265
182. Talwalkar MA. 1981. Association of infant mortality and high fertility: an empirical investigation. *International Institute for Population Sciences Newsletter* 22:2-11
183. Zahra F, Haberland N, Psaki S. 2022. PROTOCOL: causal mechanisms linking education with fertility, HIV, and child mortality: a systematic review. *Campbell Systematic Reviews* 18:e1250
184. van Soest A, Saha UR. 2018. Relationships between infant mortality, birth spacing and fertility in Matlab, Bangladesh. *PLoS One* 13:e0195940
185. Saha UR, van Soest A. 2013. Contraceptive use, birth spacing, and child survival in Matlab, Bangladesh. *Studies in Family Planning* 44:45-66
186. Koenig MA, Hossain MB, Whittaker M. 1997. The influence of quality of care upon contraceptive use in rural Bangladesh. *Studies in Family Planning* 28:278-289
187. Joshi S, Schultz TP. 2013. Family planning and women's and children's health: long-term consequences of an outreach program in Matlab, Bangladesh. *Demography* 50:149-180
188. Agha S, Do M. Sohail Agha and Mai Do. 2010. The quality of family planning services and client satisfaction in the public and private sectors in Kenya. *International Journal for Quality in Health Care* 21:87–96
189. Aghajanian A. 1995. A new direction in population policy and family planning in the Islamic Republic of Iran. *Asia-Pacific Population Journal* 10:3-20
190. Hoodfar H, Assadpour S. 2000. The politics of population policy in the Islamic Republic of Iran. *Studies in family Planning* 31:19-34

Supplementary Information

Appendix 1. Literature review of population density, overpopulation, and child health outcomes

A PubMed search on 8 April 2024 using the terms “population density” OR “overpopulation” & “child health”, between 2015 and 2024, yielded 84 results. After screening the full papers, we identified 40 papers showing an effect of population density on child-health outcomes. We discuss these reported effects of population on pregnancy, infants, children specifically, and children as part of the larger population.

Three papers assessed the impacts of population density on pregnancy outcomes. In the developing region of Tibet, low population density was directly associated with low healthcare coverage and poor maternal outcomes during pregnancy (1). However, this outcome was directly related to access to healthcare rather than population density itself. In the high-income region of North Carolina, USA, higher population density was correlated with lower rates of teenage pregnancy; however, ethnicity, poverty, and education had larger effects on rates of teenage pregnancy and the reasons why population density influenced teenage pregnancy was not discussed (2). A study of pregnant women in New York, USA, reported no statistical evidence for an association between SARS-CoV-2 infection and population density (3).

We found three papers examining infants. A Tanzanian study investigating the effects of urbanisation on neonatal and perinatal mortality revealed an increased risk with increasing population density, independent of travel time to the nearest hospital (4). A study from Ghana found higher population density was correlated with reduced neonatal mortality, likely associated with increased maternal health coverage (5). The third study from Canada assessed fungal contamination of human milk, finding lower contamination in lower-density populations (6). Another 26 studies reported effects of population density on child-health outcomes, including mortality and overall health, nutrition outcomes, factors associated with safe drinking-water, sanitation and hygiene, vaccination, and vector-borne diseases, among others.

Among 172 low- and middle-income countries, higher population density amplified childhood stunting and mortality by increasing the negative influence of poor sanitation (7). Increasing population density was negatively associated with under-five mortality in Ethiopia, with this effect likely related to healthcare coverage (8). A composite child health index derived for countries across Africa revealed declining child health outcomes were associated with increasing household size, a proxy for population density (9).

Prevalence of childhood stunting (10), wasting (11), and being underweight (12) in Ethiopia declined with increasing population density, which was related to healthcare coverage and availability rather than population itself. Adolescent height was positively correlated with higher population density in China, likely reflecting lower poverty and more accessibility to health services (13). In contrast to the undernutrition studied in low-income countries, childhood obesity is more commonly studied in high-income countries. Lower population density was associated with higher body mass index in Norway, attributed to lifestyle differences in urban *versus* rural areas (14). Conversely, in a paediatric cohort in Philadelphia, USA, increasing population density was correlated with a lower 'greenness' score that contributed to increases in body-mass index (15).

Improved water, sanitation, and hygiene improve child health; however, high population density and unplanned development of water supply and sewerage system can cause high enteric disease in children in Bangladesh (16), with the effects of good sanitation reducing diarrhoea amplified as population density increases (17). A global review of childhood diarrhoea due to *Cryptosporidium* reported a positive correlation with population density (18). Overcrowding was identified as a risk factor for soil-transmitted helminth infection in children in the Philippines (19).

Childhood vaccination coverage was positively associated with population density in Ethiopia (20, 21) and Pakistan (22). Again, the common theme of higher population density related to healthcare coverage in lower-income countries was the mechanism of improved child health, rather than a reflection of population itself. Similarly, compared to regions with low population density in Senegal, the probability of complete immunisation was higher in regions with intermediate population density, but higher population densities did not increase vaccination coverage further (23), indicating the existence of a minimum threshold of healthcare coverage for improved immunisation outcomes in children, rather than population density alone affecting this outcome.

Two papers reported the effects of population density on dengue infection in children. A study in Thailand found that transmission was positively correlated with population density (24), and in Indonesia higher odds of seropositivity to dengue was associated with higher population density (25).

There are several other reported child-health outcomes related to population density. In low-income countries or socially disadvantaged communities, higher population density was associated with poorer outcomes for children, while the opposite effects have been reported in high-income settings. In India, higher population density correlated with increased risk of being predisposed to diabetes (26). In the slums of Haiti, high population density was linked to high incidences of respiratory and gastrointestinal illness in children under five years of age (27). In a disadvantaged community in the USA, high population density was linked to increased crime and low education, and resulted in lower cognitive abilities, higher body-mass index, and more sleep disorders in children (28).

The following studies from high-income countries reported beneficial effects of higher population density on child health outcomes. In England, higher population density was associated with a slightly lower rate of hospital admissions for children with bronchiolitis (29). A Western Australian study on child development reported lower odds of physical vulnerability were associated with increased residential density (30). In Ontario, Canada, higher population density decreased the odds of binge-drinking in adolescents (31). In Finland, higher incidence rates of paediatric irritable bowel disease were associated with regions with lower density of child population (32).

Eight other studies reported the impacts of population density on population health, including children. Higher population density is a risk factor for disease transmission globally, including for zoonotic infections (33) and COVID-19 (34), with transmission worse in slums with a higher proportion of young people. In India (35) and Indonesia (36), high population density increased the risk of dengue infection, which disproportionately affects children over five years of age. Typhoid outbreaks in Malawi were associated with increasing population density (37). In China, another consequence of higher population density is more air pollution and the resultant higher burden of disease via more people being exposed to that pollution (38). In contrast, lower population density was linked to lower risk of developing irritable bowel disease in Canada, with the association strongest in young children and adolescents (39). In Haiti, higher population density was one of the correlates of seeking conventional treatment when sick (40), likely a consequence of reduced barriers to healthcare rather than a direct effect of population size.

Overall, the effects of population on child health outcomes vary greatly depending on a country's relative income. High population density in lower-income countries is linked to both negative and positive child health outcomes; however, every positive child health outcome was facilitated by increased access to healthcare rather than a direct benefit from population density itself. Those directly related to population density show increasing population density worsened child health in lower-income countries. Because most future children will be born in developing countries (see main text), there is a disproportionate negative effect of higher population densities on most children worldwide. Population density also had mixed effects on child health in higher-income countries; however, it appears that these children are buffered from many of the worst health outcomes.

References

1. Labasangzhu, Bjertness E, McNeil EB, et al. 2018. Progress and challenges in improving maternal health in the Tibet Autonomous Region, China. *Risk Management and Healthcare Policy* 11:221-231
2. Bennett CA, Delamater PL. 2020. Travel time to title X facilities and teenage birth rates in North Carolina. *Maternal and Child Health Journal* 24:953-959
3. Emeruwa UN, Ona S, Shaman JL, et al. 2020. Associations between built environment, neighborhood socioeconomic status, and SARS-CoV-2 infection among pregnant women in New York City. *Jama* 324:390-392
4. Macharia PM, Beňová L, Pinchoff J, et al. 2023. Neonatal and perinatal mortality in the urban continuum: a geospatial analysis of the household survey, satellite imagery and travel time data in Tanzania. *BMJ Global Health* 8:
5. Dwomoh D. 2021. Geospatial analysis of determinants of neonatal mortality in Ghana. *BMC Public Health* 21:492
6. Moossavi S, Fehr K, Derakhshani H, et al. 2020. Human milk fungi: environmental determinants and inter-kingdom associations with milk bacteria in the CHILD Cohort Study. *BMC Microbiology* 20:146
7. Hathi P, Haque S, Pant L, Coffey D, Spears D. 2017. Place and child health: the interaction of population density and sanitation in developing countries. *Demography* 54:337-360

8. Atalell KA, Alene KA. 2023. Spatiotemporal distributions of under-five mortality in Ethiopia between 2000 and 2019. *PLoS Global Public Health* 3:e0001504
9. Bradshaw CJA, Otto SP, Mehrabi Z, et al. 2019. Testing the socioeconomic and environmental determinants of better child-health outcomes in Africa: a cross-sectional study among nations. *BMJ Open* 9:e029968
10. Atalell KA, Techane MA, Terefe B, Tamir TT. 2023. Mapping stunted children in Ethiopia using two decades of data between 2000 and 2019. A geospatial analysis through the Bayesian approach. *Journal of Health, Population and Nutrition* 42:113
11. Atalell KA, Dessie MT, Wubneh CA. 2023. Mapping wasted children using data from the Ethiopia Demographic and Health Surveys between 2000 and 2019: A bayesian geospatial analysis. *Nutrition* 108:111940
12. Atalell KA, Alemu TG, Wubneh CA. 2022. Mapping underweight in children using data from the five Ethiopia Demographic and Health Survey data conducted between 2000 and 2019: a geospatial analysis using the Bayesian framework. *Frontiers in Nutrition* 9:988417
13. Zhang Y, Wang H, Wang X, et al. 2019. The association between urbanization and child height: a multilevel study in China. *BMC Public Health* 19:569
14. Øvrebø B, Bergh IH, Stea TH, et al. 2021. Overweight, obesity, and thinness among a nationally representative sample of Norwegian adolescents and changes from childhood: Associations with sex, region, and population density. *PLoS One* 16:e0255699
15. Daniels K, Lê-Scherban F, Auchincloss AH, et al. 2021. Longitudinal associations of neighborhood environment features with pediatric body mass index. *Health Place* 71:102656
16. Saha S, Saha S, Das RC, et al. 2018. Enteric fever and related contextual factors in Bangladesh. *American Journal of Tropical Medicine and Hygiene* 99:20-25
17. Contreras JD, Islam M, Mertens A, et al. 2022. Influence of community-level sanitation coverage and population density on environmental fecal contamination and child health in a longitudinal cohort in rural Bangladesh. *International Journal of Hygiene and Environmental Health* 245:114031
18. Lal A, Fearnley E, Wilford E. 2019. Local weather, flooding history and childhood diarrhoea caused by the parasite *Cryptosporidium* spp.: a systematic review and meta-analysis. *Science of the Total Environment* 674:300-306
19. Owada K, Lau CL, Leonardo L, et al. 2018. Spatial distribution and populations at risk of *A. lumbricoides* and *T. trichiura* co-infections and infection intensity classes: an ecological study. *Parasites and Vectors* 11:535
20. Asmare Atalell K, Asmare Techane M, Adugna Wubneh C, et al. 2022. Spatiotemporal distributions of immunization coverage in Ethiopia from 2000 to 2019. *Vaccine* 40:1413-1420
21. Atalell KA, Alemayehu MA, Teshager NW, et al. 2022. Mapping BCG vaccination coverage in Ethiopia between 2000 and 2019. *BMC Infectious Diseases* 22:569
22. Chen X, Porter A, Abdur Rehman N, Morris SK, Saif U, Chunara R. 2023. Area-based determinants of outreach vaccination for reaching vulnerable populations: a cross-sectional study in Pakistan. *PLoS Global Public Health* 3:e0001703
23. Cortaredona S, Diop R, Seror V, Sagaon-Teyssier L, Peretti-Watel P. 2020. Regional variations of childhood immunisations in Senegal: a multilevel analysis. *Tropical Medicine and International Health* 25:1122-1130
24. Salje H, Lessler J, Maljkovic Berry I, et al. 2017. Dengue diversity across spatial and temporal scales: local structure and the effect of host population size. *Science* 355:1302-1306
25. Tam CC, O'Driscoll M, Taurel AF, Nealon J, Hadinegoro SR. 2018. Geographic variation in dengue seroprevalence and force of infection in the urban paediatric population of Indonesia. *PLoS Neglected Tropical Diseases* 12:e0006932
26. Wells JC, Pomeroy E, Walimbe SR, Popkin BM, Yajnik CS. 2016. The elevated susceptibility to diabetes in India: an evolutionary perspective. *Frontiers in Public Health* 4:145
27. McNairy ML, Tymejczyk O, Rivera V, et al. 2019. High burden of non-communicable diseases among a young slum population in Haiti. *Journal of Urban Health* 96:797-812
28. Xiao Y, Mann JJ, Chow JC, et al. 2023. Patterns of social determinants of health and child mental health, cognition, and physical health. *JAMA Pediatrics* 177:1294-1305
29. Lewis KM, De Stavola B, Hardelid P. 2020. Geospatial and seasonal variation of bronchiolitis in England: a cohort study using hospital episode statistics. *Thorax* 75:262-268
30. Bell MF, Turrell G, Beesley B, et al. 2020. Children's neighbourhood physical environment and early development: an individual child level linked data study. *Journal of Epidemiology and Community Health* 74:321-329
31. Larsen K, To T, Irving HM, et al. 2017. Smoking and binge-drinking among adolescents, Ontario, Canada: does the school neighbourhood matter? *Health Place* 47:108-114
32. Lehtinen P, Pasanen K, Kolho KL, Auvinen A. 2016. Incidence of pediatric inflammatory bowel disease in Finland: an environmental study. *Journal of Pediatric Gastroenterology and Nutrition* 63:65-70
33. Proboste T, James A, Charette-Castonguay A, et al. 2022. Research and innovation opportunities to improve epidemiological knowledge and control of environmentally driven zoonoses. *Annals of Global Health* 88:93
34. von Seidlein L, Alabaster G, Deen J, Knudsen J. 2021. Crowding has consequences: prevention and management of COVID-19 in informal urban settlements. *Building and Environment* 188:107472

35. Swain S, Bhatt M, Pati S, Soares Magalhaes RJ. 2019. Distribution of and associated factors for dengue burden in the state of Odisha, India during 2010-2016. *Infectious Diseases of Poverty* 8:31
36. Dhewantara PW, Marina R, Puspita T, et al. 2019. Spatial and temporal variation of dengue incidence in the island of Bali, Indonesia: an ecological study. *Travel Medicien and Infectious Disease* 32:101437
37. Pitzer VE, Feasey NA, Msefula C, et al. 2015. Mathematical modeling to assess the drivers of the recent emergence of typhoid fever in Blantyre, Malawi. *Clinical Infectious Diseases* 61 Suppl 4:S251-8
38. Meng X, Wang W, Shi S, et al. 2022. Evaluating the spatiotemporal ozone characteristics with high-resolution predictions in mainland China, 2013-2019. *Environmental Pollution* 299:118865
39. Benchimol EI, Kaplan GG, Otley AR, et al. 2017. Rural and urban residence during early life is associated with risk of inflammatory bowel disease: a population-based inception and birth cohort study. *American Journal of Gastroenterology* 112:1412-1422
40. Klarman M, Schon J, Cajusma Y, et al. 2021. Opportunities to catalyse improved healthcare access in pluralistic systems: a cross-sectional study in Haiti. *BMJ Open* 11:e047367