Transgression of planetary boundaries and the effects on child health through an infectious diseases lens

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REVIEW

Transgression of planetary boundaries and the effects on child health through an infectious diseases lens

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Purpose of review
Life on earth, as we know it, is changing. The likelihood of more frequent pandemics and disease outbreaks is something that current global healthcare infrastructure is ill equipped to navigate. Human activity is forcing our planet into a new geologic epoch, the Anthropocene, which is typified by increased uncertainty resulting from human disruption of earth's life-giving ecosystems. Plagues and pandemics have always been unfortunate partners to periods of disruption, as they will be again if the frequency and severity of climate and conflict-mediated disasters increase in coming years. If we continue to exceed and degrade the planetary boundaries that protect human health, our children and their children will reap the consequences.

Recent findings
Scientists have defined nine 'safe operating' planetary boundaries for life in all its glorious diversity to thrive on planet earth. Recent evidence suggests that six of these nine boundaries have already been transgressed, but the potential implications for these transgressions upon child health is not well articulated. We highlight how contravention of these boundaries will impact infectious disease risk and humans' ability to survive and thrive. We reflect specifically on how paediatricians are called upon to speak up for the most vulnerable members of our species, young children and as yet unborn future generations.

Summary
Post COVID-19 initiatives to improve pandemic preparedness and response are certainly warranted, but pandemic prevention should include committed efforts not to exceed safe planetary boundaries. Willingly exceeding these boundaries has deep moral consequences that are poorly articulated by current ethical frameworks. Paediatricians are best placed to develop and champion the neglected 'third dimension' of medical ethics, recognizing the moral imperative to protect the long-term best interests of children and future generations.

Keywords
children, climate change, communicable disease, infectious disease, paediatric, planetary boundaries, planetary health

INTRODUCTION

While all life on earth is affected by climate change, children and future generations will experience the brunt of the adverse impact if current generations (we) continue to transgress well defined 'safe planetary boundaries' [1]. Nine systems underlie human health and survival on planet earth (Fig. 1). There are clear and measurable boundaries for these life-sustaining systems which enable quantification of the planet's remaining 'shock-absorbance' before key systems are perturbed to an extent that threatens its ability to sustain life in all its abundance, that is, the world that we know in which modern

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KEY POINTS

- We outline how planetary boundary transgression impacts infectious disease and child health.
- The planetary boundaries define well tolerated conditions for the life and health of children on earth.
- Six-of-nine planetary boundaries are transgressed, destabilizing infectious disease dynamics.
- This is the greatest current threat to child health, and it is underrecognized by paediatricians.
- Climate-sensitive paediatric practice is a dimension of the ethical mandate to protect children.

humans evolved [2■■]. These boundaries incorporate climate-change, measured as carbon dioxide parts per million as a single representative metric, but also include a consideration of all critical systems impacted by human activity that directly or indirectly influence human health and wellbeing [3,4]. Transgression of these conditions will have long-term impacts upon the environments in which children live, grow and play, adversely affecting their health (Table 1) [153–209]. From an infectious diseases perspective, environmental changes can create conditions that favour pathogen (re)emergence and spread, magnified by increased host vulnerability [5].

Currently, six-out-of-nine planetary boundaries are transgressed, with the effects on infectious disease and child health already observable in our world. Infectious diseases classically understood to be climate-sensitive, such as vector-borne diseases (transmitted by ticks, mosquitos, etc.) and those with wild (bats, rodents, birds, etc.) or domesticated (chickens, pigs, cattle, cats and dogs, etc.), animal reservoirs are currently extending their distribution to new regions, due to more favourable climate conditions and habitat loss that forces closer human-animal contact or facilitated breeding in human occupied spaces [6–11]. This amplifies current signals which indicate that children are already disproportionately affected by vector-borne pathogens and other climate-sensitive infections [12,13].

In addition, we are also seeing diseases which are not considered 'typical' climate sensitive infections that are increasingly impacted by human-induced climate change and its secondary effects [14–16]. Concerningly, this includes diseases like tuberculosis, which remains the leading infectious disease killer on the planet, imposing the highest mortality amongst vulnerable young children [17,18]. Interruptions in childhood vaccination (including immunisation against tuberculosis with *Bacille-Calmette Guerin* (BCG), alongside inadequate measles vaccine coverage and case detection occasioned by displacement [19–21], war and natural disasters – all of which are aggravated by the contravention of planetary boundaries – pose major risks for child health. The impact of more childhood infections caused by novel pathogens with less available diagnostics and treatments poses a serious healthcare and research challenge, and may limit the ability to deliver effective care in an equitable way [13,22].

By characterizing the possible infectious disease and child health outcomes linked to the transgression of each planetary boundary, within this review article, we construct a risk scaffold that may assist awareness and promote mitigation of these outcomes in a world beyond planetary boundaries. We also present an ethical framework that incorporates the neglected 'third dimension' of medical ethics (Fig. 2), which has particular relevance to paediatricians, whose role includes protecting (and advocating for) the health of vulnerable children.

PLANETARY BOUNDARIES FOR HUMAN HEALTH

The nine planetary boundaries (summarised in Fig. 1) are 'safe operating conditions' for life on planet earth [2■■]. These defined and measurable systems are climate change, freshwater change, biogeochemical flows, land system change, ozone depletion, biosphere integrity, ocean acidification, novel entities and aerosol loading. In 2024, six-out-of-nine of these boundaries are transgressed. How these boundaries are measured, their current status and the present-day and future effects of their transgression on infectious diseases and child health are outlined for each planetary boundary in Table 1. Importantly, the intensification of infectious disease risk for children in our world beyond planetary boundaries is mediated through three main effects, explored below.

Expanded pathogen reservoirs and vectors with opportunity for cross-species transmission

Contravention of planetary boundaries elevates the risk of catastrophic events which, in turn, create ideal transmission environments for infectious disease [23]. This is mediated through destabilisation of health, water and sanitation infrastructure, crowding and inadequate housing through poverty or displacement, which reduces hygiene and the ability to protect against extremes in temperature. War is an important outcome of contravened planetary

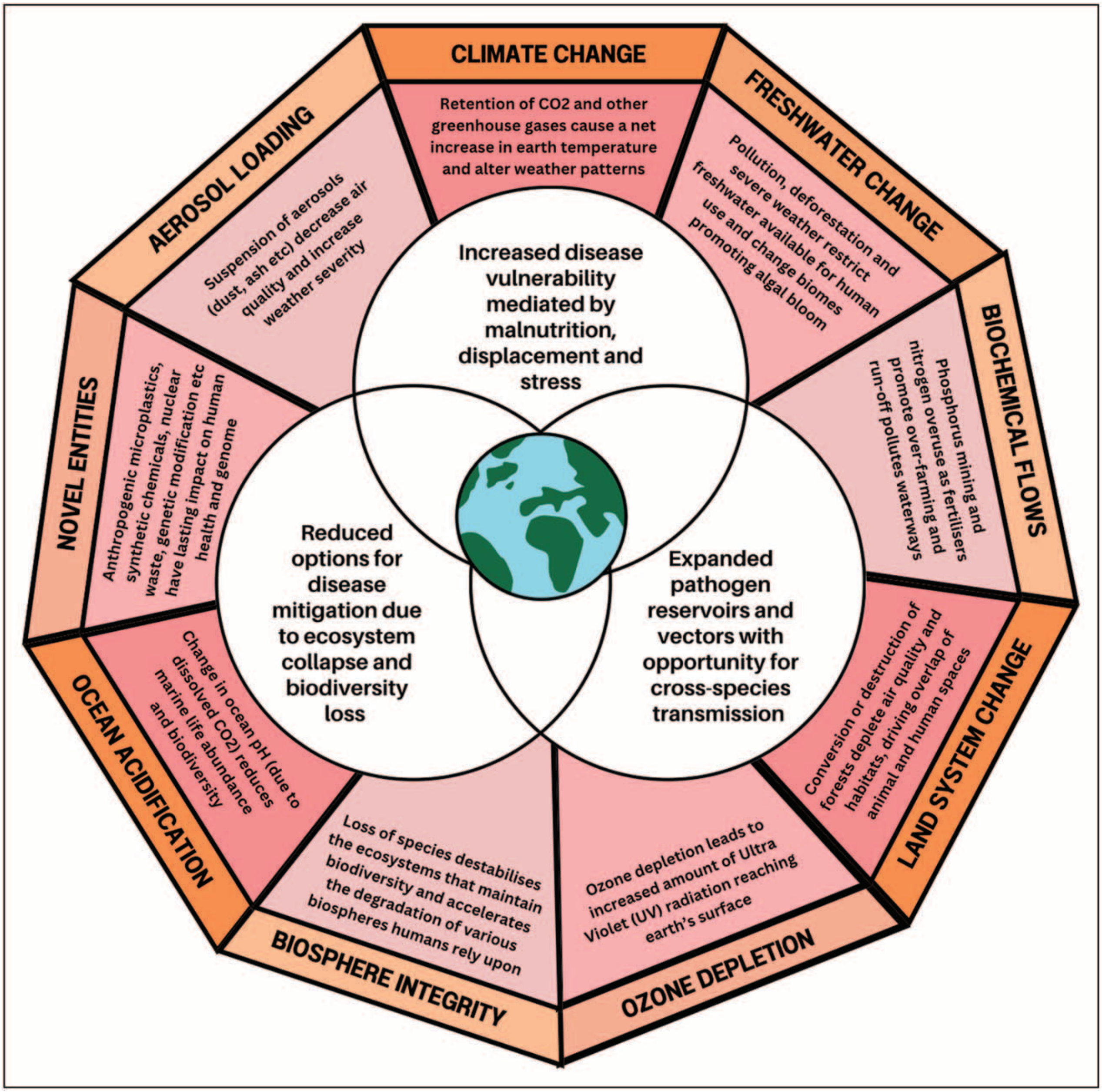

FIGURE 1. Overview of the nine planetary boundaries and the three intermediaries by which their transgression impacts human health. Adapted from [2••].

boundaries as competition for dwindling resources turns violent [24–27]. A current example is the polio epidemic in war-torn Gaza, where children have been the innocent victims of indiscriminate destruction of civilian life, with unprecedented disruption to basic health and humanitarian services [28–30]. Climate-mediated changes in the abundance and distribution of disease vectors, as well as environmental and nonhuman host pathogen reservoirs also increase the likelihood of human infection and sustained transmission. An example is the broadening range of mosquito-borne diseases, including dengue, chikungunya and zika that are transmitted by the *Aedes aegypti* and *Aedes albopictus* mosquitoes, which are highly adapted to human environments [31–34].

Reduced options for disease mitigation due to ecosystem collapse and biodiversity loss

A loss of biodiversity resulting from human-induced climate change decreases the opportunities we as a species have to mitigate pathogen-mediated climate effects [35]. For example, destruction of soil and marine diversity reduces the future sources of antibiotic discovery as well as food security [36–42].

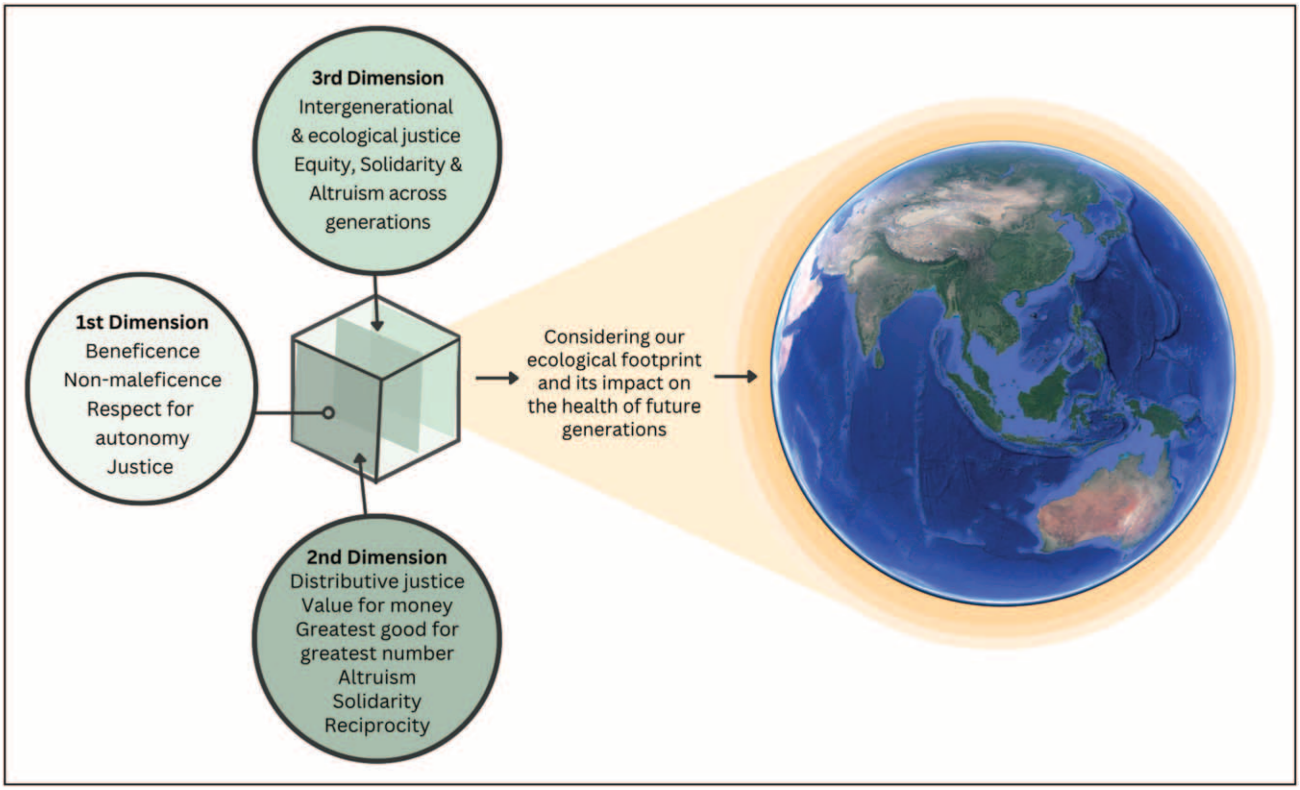

FIGURE 2. Articulating the third dimension of medical ethics and considering the future health impact of our ecological footprint. Adapted from [146■■].

Reductions in 'soil health' and a shift to global monocrops increases the risk of agricultural industry instability, famine and loss of important dietary variety in the event of crop blight. History has already yielded examples of this, such as Panama disease (*Fusarium oxysporum*) in the 1950 s almost entirely wiping out the then globally dominant cultivar of Gros Michel banana, with a new strain outbreak threatening today's Cavendish banana crop around the world [43,44]. Habitat destruction and biodiversity loss further leads to loss of 'niche adaptation', with disrupted competition and predation feedback loops, leading to an overabundance of disease-spreading species, such as rats, and vectors such as mosquitos with increased human contact and zoonotic disease spillover risk [45–49]. Current estimates indicate that children already carry 90% of the disease burden caused by biodiversity collapse, as the top causes of global child mortality – malnutrition, neonatal deaths, respiratory infections, diarrhoea and malaria – are exacerbated by these dynamics [50,51].

Increased disease vulnerability mediated by malnutrition and stress

A major impact of the transgression of planetary boundaries is the dwindling of soil health as an essential agricultural resource, the uneven global distribution of healthy and affordable food, and the decreasing nutritional value of foods marketed for children [41,52■,53]. Many of the most intransigent infections of childhood have strong correlations with undernutrition, including tuberculosis [54,55], malaria [56,57], HIV [58], respiratory [59] and diarrheal diseases [60,61]. Critically, childhood undernutrition impacts a child's health trajectory into adulthood [62,63]. Many of today's chronic adult health challenges have their origins in nutritional deficiencies during critical periods of foetal and childhood development [64–66], promoting and complicating many noncommunicable diseases, as well as impaired cognitive outcomes and emotional wellbeing [67–69].

While not a direct climate-related impact, the seemingly unstoppable transgression of recognized 'planetary boundaries' and the climate anxiety this places upon young people [70–72], even if they are reasonably untouched by the extreme effects, causes stress that undermines immune integrity with an increased risk of both communicable and noncommunicable disease [73,74]. The COVID-19 pandemic demonstrated how the direct and indirect effects of a pandemic can trigger mental ill-health in young people [75], reducing the resilience needed to overcome the increasing daily challenge of life in the Anthropocene.

Table 1. Overview of the nine planetary boundaries and their projected impact on infectious diseases in children

Planetary boundary [2••]	Potential impact on infectious disease and child health
1. Climate change *Boundary*: *≥350 CO_2 parts per million* *Status*: Transgressed, currently 417 parts per million CO_2 and on a rapidly rising trajectory *Effect:* Production of CO_2 and other greenhouse gases faster than they can be eliminated or stored causes a net increase in temperature with alteration of weather patterns [153].	Extreme weather events reduce food security and quality leading to increased malnutrition [154,155]. Increased CO_2 may reduce micro- and macronutrient composition in crops, limiting the nutritional value of available foods [27,29,156–159]. Maternal undernutrition [160] and childhood stunting mediated by food insecurity increases vulnerability to infectious diseases (tuberculosis is a key exemplar [54]) and influence chronic disease in later life [62,63,69,161]. Changing climate expand the distribution of key disease vectors, such as mosquitos and ticks, with less disease-adapted human populations exposed to new diseases (such as malaria spreading into southern Europe or Dengue into southern parts of the US) [33,162]. Severe weather events and the resultant disruption of livelihoods cause mass migration ('climate refugees') with more intense resource competition creating conditions for conflict and war. Conflict-mediated displacement foment vulnerability and exposure to infectious disease outbreaks [27,29,158].
2. Ocean acidification *Boundary:* ≥80% of the preindustrial averaged global surface saturation of aragonite (≥80% of 3.44 Ω_{arag}) *Status:* Currently within safe operating margin (2.8 Ω_{arag}), but worsening *Effect:* Change in ocean pH (due to dissolved CO_2) leads to coral erosion, carbonate dissolution and a reduction in marine life and biodiversity [163].	Ocean acidification alters marine ecology, increasing the damage done to coral reefs, decreasing fish abundance and increasing the likelihood of harmful infections (especially in aquafarming) [164–167]. Reduced fish stocks limit healthy macronutrient (especially protein) availability. Pacific Island communities are particularly vulnerable [168–170]. Increased heavy metal pollution, such as mercury which accumulates in apex predator species, is particularly harmful to pregnant mothers and impact the cognition and cardiovascular disease risk of their children [171]. Loss of marine biodiversity reduces opportunity for drug discovery, as marine organisms form an important source for novel antibiotics and often perform unique metabolic functions that could be of great societal value [36–39].
3. Stratospheric ozone depletion *Boundary:* ~276 dobson units (DU) *Status:* Currently within well tolerated operating margin (284.6 DU), with fragile recovery *Effect:* Ozone depletion leads to an increased amount of ultraviolet (UV) radiation reaching earth's surface, resulting in increased cellular damage and stress.	UV has a complex relationship with human health that is not solely dependent on the way in which UV is needed to promote vitamin D production in humans. Overexposure to UV light causes skin cancer, yet simultaneously reduces autoimmunity. UV light also helps to inactivate infectious particles in the air and in drinking water for example. This boundary is not transgressed, but requires ongoing close monitoring given its risk for serious health effects, even if these are somewhat variable effect on [172–174].
4. Biogeochemical flows *Boundary:* ≥11 teragrams (Tg) of phosphorus and/or ≥62 Tg of nitrogen per year applied to agricultural land *Status:* Transgressed, currently 22.6 Tg of phosphorus per year and 190 Tg of nitrogen per year with a rising trajectory *Effect:* Applying the Haber-Bosch process on an industrial scale enabled widespread use of N-based fertilisers that increase agricultural productivity, but excessive nitrogen or phosphorus has multiple detrimental impacts	Although N-based fertilisers helped to fuel the so-called 'green revolution' in agriculture that increased food security in recent decades, its positive effect has likely reached saturation whereas the negative effects of continue to intensify [175]. The positive effect of phosphorus use in agriculture also has limits and excessive environmental pollution, fuels water eutrophication and toxic algal blooms [176]. With both nitrogen and phosphorus, a careful balance must be struck for optimal and sustained agricultural productivity, without excessive environmental pollution and damage freshwater and marine ecosystems.

Table 1 (*Continued*)

Planetary boundary [2■■]	Potential impact on infectious disease and child health
5. Novel entities *Boundary:* >80% of synthetic chemicals released into the environment do not have adequate safety testing *Status:* Transgressed, currently very limited mandatory safety testing or oversight of novel compounds, as seen with the 'forever chemical' fiasco *Effect:* Entities that would not exist in the Earth natural system in the absence of human activity. Novel entities include plastics, synthetic chemicals, and genetically modified organisms.	In addition to their toxic impact on marine life (and the distal human health impacts of this on food) and human fertility [177], microplastics act as fomites to perpetuate survival of infectious diseases in the environment, serving as a potential new route for infectious disease transmission [178–180]. Larger synthetic objects such as plastic bottles or car tyres provide nesting grounds for the human adapted *Aedes* mosquito [181], while plastic pollution in the sea provides a major threat to wild life and the ecosystem services that they provide. A truly novel risk of the modern era is the temptation to improve child resilience against infectious disease through germline genetic editing. In 2018, genetic material was introduced into two human embryos using clustered regularly interspaced short palindromic repeats (CRISPR) technologies in an attempt to promote resistance against HIV infection [182–184]. The scandal that erupted highlights the extreme helplessness of children and the fact that they carry the burden of unregulated industries and inconsiderate ethical standards.
6. Freshwater change *Boundary:* 10.2% of all surface or ground freshwater ('blue water') or 11.1% of soil water available for plant use ('green water') has changes in water availability or safety. *Status:* Transgressed. currently 18.2% of blue water and 15.8% of green water have rapidly deteriorating safety and availability [185] *Effect:* Change in safe freshwater availability due to pollution, overextraction or severe climate events restrict human access and adversely affect critical freshwater biomes.	The disturbance of freshwater flows by human activity includes the loss of fresh water due to deforestation and the destruction of riparian forest margins that are crucial to freshwater biodiversity. Overuse of local fresh water resources often result in food insecurity, conflict and forced migration The pollution of freshwater streams due to nitrogen/phosphorus run-off, or sewerage contamination further reduce this precious resource and al its lifegiving attributes. Key infectious diseases that thrive in freshwater when flow is disrupted or pollution introduced include cholera, typhoid, dysentery, E.coli and other diarrhoeal diseases, as well as leptospirosis and the harmful effects of algal blooms on fresh water life or direct toxicity if ingested. Children are especially at risk from these diseases as poor hygiene and sanitation literacy/ habits may lead them to consume unsafe waters more frequently than adults [186].
7. Land system change *Boundary:* <75% of potential global forestland remains relative to original forest cover. *Status:* Transgressed, currently only 60% of global forests remain with no slowdown in deforestation rates. *Effect:* Deforestation destroys important biodiversity 'hot spots', destroying carbon sinks and freshwater resources, with reductions in air quality and increased risk of disease emergence given close contact between stressed wild animals, abundant disease-vectors and human settlements [187,188].	Major forest clearing for agricultural purposes and destruction by fires critically increase the risk of emergent / re-emergent disease spillover into human populations as wild places and human places abut [45,189,190]. Examples include coronavirus and other emergent diseases [191,192] as well as many vector-borne diseases [11,193].
8. Biosphere integrity *Boundary:* <10 E/MSY (extinctions per million species-years) *Status:* Transgressed, currently >100 E/MSY *Effect:* Critical species loss destabilise interconnected ecosystems that maintain overall biodiversity and planetary health. The degradation of various biospheres that diverse species and their functions maintain is often invisible, until critical thresholds are crossed with biosphere collapse or there is radical ecosystem reorientation [194,195].	An accelerated extinction rate has severe effects upon human nutrition, as a loss of pollinators severely limit the food security in communities and the nutritional quality of available food crops [196–200], with implications for immune resilience against infectious disease in undernourished children [5]. Extinctions are also implicated in the loss of novel compounds for medical use to combat infectious disease [36,38,40], thereby limiting opportunities to mitigate future impact of the emerges of microbial resistance against current antibiotics. Loss of specialised environments reduce the abundance and variety of specialist species, many of whom are natural competitors / predators of more generalist species (rats, pigeons etc) that can thrive in human environments and are established sources of zoonotic disease [201–204].

Table 1 (*Continued*)

Planetary boundary [2■■]	Potential impact on infectious disease and child health
9. Atmospheric aerosol loading *Boundary:* Difference in aerosol optical depth (AOD) ≥ 0.1 *Status:* Currently within well tolerated operating margin (AOD 0.076) and worsening *Effect:* Suspended aerosols (such as internal combustion particles, coal dust, fire smoke etc) decrease air quality overall and is closely linked to chronic lung disease, as well as cardiovascular disease and stroke. In addition, air pollutants also influence weather events, e.g. high AOD reduces rainfall in monsoon regions but may increase rainfall intensity in other regions.	The association between increased atmospheric loading of both biogenic and man-made aerosols in reducing rainfall is not fully understood [117,205–207]. However, the impact of low rainfall during rainy seasons upon food availability and famine in those regions – including the acute impact on children – is well established. Drought is also associated with increased risk behaviours for sexually transmitted diseases (for example, HIV [100,103]) which highlights how catastrophic weather events can lead to the creation of high-transmission environments beyond zoonotic and vector-borne routes of transmission. Increased aerosol loading in areas prone to dust storms or fires, for example, also leads to impaired lung health and enhanced susceptibility to aerosol/respiratory infections such as pneumonia and tuberculosis [117,205–208]. Children are at particular risk of deleterious effects of ambient air pollutant exposure due to the immaturity of their lung development and tendency for greater exposure than adults due to higher baseline ventilation rate and generally spending more time outdoors [209].

A summary of the nine planetary boundaries, the consequences of exceeding these well tolerated operating parameters for life on earth, and the impact upon infectious diseases and child health are explored in Table 1.

EXMPLARS OF DISEASE OUTBREAKS LINKED TO HUMAN ENVIRONMENTAL MANIPULATION: THROUGH THE AGES

Prehistory

Many historical infectious disease outbreaks can be linked to early human environmental manipulation, although this was not on the scale we are witnessing in the twenty-first century. Perhaps one of the earliest examples is the emergence of *Mycobacterium tuberculosis*, which remains the leading infectious disease killer on the planet [76]. The evolution of *M. tuberculosis* from a soil-dwelling mycobacterium to a human respiratory pathogen spread via the aerosol route [77], was likely closely linked to *Homo sapiens* being the only species to have controlled fire [78]. The control of fire represents the first step in our 'mastery' of nature, starting the journey of scientific progress that continues to provide huge opportunities and benefits, as well as accompanying challenges with unsustainable environmental impacts the most pressing issue.

Medieval

Since ancient times, human trade and travel, including the slave trade, have exposed new ecosystems and populations to disease, allowing epidemics to spread beyond their natural distribution. In Medieval times, global trade and travel seeded such notorious outbreaks as the Plague of Justinian (also the Black Death and Bubonic Plague) (*Yersinia pestis*) [79,80] and smallpox [81] and spread leprosy (*Mycobacterium leprae)* [82] across the globe. Fuelled by famine and 'exotic' tastes, human encroachment in wild spaces and trade of wild species and bush meats in wet markets have been implicated as sources for more recent pandemics like coronavirus-19 and HIV [83,84], the latter having devastating effects upon the health of children and young people, creating the largest orphan crisis in living memory [85,86].

Industrial revolution

Human-mediated changes to land use and intensive farming practices augmented by the Industrial Revolution, both in terms of stock density (e.g. 'battery' poultry farming or cattle feedlots) and in terms of unnatural diets (e.g. the recycling of animal 'waste parts' as feed supplements or antibiotic as a routine additive in livestock feed) have led to various zoonotic infectious disease outbreaks. In modern times, these include highly pathogenic Avian Influenza or Bird Flu (H5N1) [87,88] and bovine spongiform encephalopathy (BSE; colloquially known as 'Mad Cow' disease) [89,90]. Excessive use of antibiotics in farming practices, such as routine antibiotic use in cattle feedlots or fungicide use in agriculture, is fuelling the selection of drug-resistant human pathogens [35,91]. A particularly worrying example is the high rates of *Escherichia coli* resistance to the 'last resort' antibiotic, colistin, resulting from routine colistin use in pig and poultry production in certain parts of Asia [92,93].

Severe disease caused by antibiotic resistant infections is a huge problem for children in low-income settings, where tools to detect resistance may be lacking, and the variety of alternative antibiotics or treatments is limited [94].

Other human environmental manipulations associated with large-scale disease outbreaks include the 1845 Irish Potato Famine and Bilharzia/Schistosomiasis in Egypt. In Ireland, industrial scale monocrop agriculture brought severe famine when potatoes succumbed to blight, caused by *Phytophthora infestans* [95]. Many factors contributed to make poor families particularly vulnerable leading to unprecedented mortality and mass migration [96]. While not a human disease outbreak, the potential impact on human health and food security of disease affecting intensive monocrop agriculture is a persistent risk in modern times. In Egypt, extensive irrigation projects along the Nile river enabled the extensive spread of schistosomiasis (mostly *Schistosoma mansoni* and *Schistosoma haematobium*), with children aged 10–14 years the group with the highest disease prevalence and most severe acute disease manifestations [97,98].

Modern

As human-accelerated climate change increases the frequency of natural disasters, infectious disease outbreaks also increase (a well known consequence) as critical health, housing, sanitation and safe water infrastructure break down [23]. Following the devastating 2022 Pakistan floods, skin infections and diarrheal diseases increased more than 50% compared to the preflood period, with malaria and dengue cases increasing by more than 200 and 800%, respectively [99]. Worsening drought events in high HIV-incidence sub-Saharan Africa is related to an increase in transactional sex (i.e. sex-for-food exchanges) [100,101], with worse HIV antiretroviral therapy adherence and an increase in rates of condomless sex found to be highest amongst adolescents [102,103]. This is an example of the indirect effects that climate mediated disasters have on many infectious diseases. The 2022 cholera outbreak in Malawi after cyclone Freddy [104] demonstrates how historic outbreaks, such as the 1855 London cholera outbreak famously terminated by John Snow's epidemiological insights [105], are replicated when lessons learnt about water and sanitation cannot be effectively implemented.

Recent exemplars

COVID-19

Despite modern advances in medicine, pandemics pose as great a challenge as ever. In fact, given the scale and speed at which pathogens can spread in a globalized world, even the best healthcare infrastructure remains ill-equipped to deal with pandemic outbreaks. This was clearly demonstrated during the recent COVID-19 pandemic where, from the equity perspective the global community failed miserably to protect the most vulnerable people, particularly children [106▪]; whilst also failing to ensure adequate access to lifesaving vaccines and healthcare in the settings where it was needed most; posing uncomfortable questions about global solidarity and the creation of a safer world for all [107–110].

School closures implemented as a public health measure to try and reduce the spread of COVID-19 had major adverse impacts on the mental health and cognitive development of young people [106▪,111,112]. As a pandemic directly arising from wildlife trafficking and the uncontrolled selling of exotic animals and meat in wet markets [113,114], COVID-19 is a 'beast of our own making'. It represents a clear exemplar of the inherent risks and unpredictable outcomes resulting from our continued contravention of defined planetary boundaries. As the earth's well tolerated parameters for human survival and health are further eroded, future pandemics may have more disastrous impacts, also on child mortality. Maintaining a world where humans can thrive requires public health policies that are informed by child-centric medical ethics that consider and mitigate the negative 'ripple-effects' induced by crossing key planetary boundaries.

Tuberculosis

As indicated, tuberculosis is the most ancient and enduring human pandemic that is intimately linked to global inequality and the social determinants of health [76,115,116]. To this day, poor air quality with insufficient indoor ventilation creates a high risk setting for infection spread and the development of disease [117–122]. The effect of outdoor air pollution on the transmission of this respiratory pathogen are yet to be fully elucidated, but initial studies suggest poor air quality due to exhaust fumes, rice stubble burns and increased wildfires, as seen in cities like New Delhi and Jakarta, are exacerbating tuberculosis risk [123–130].

Children are at an increased risk of the negative impacts of air pollution, as their lungs are not yet fully developed and they tend to have greater relative exposure than adults due to greater physical activity and time spent outdoors, as well as a higher baseline ventilation rate [131]. Interestingly, there seems to be an association between tuberculosis incidence and local neighbourhood green spaces, independent of socioeconomic factors, and possibly mediated through improved ambient air quality [132,133].

At a global scale, undernutrition makes the greatest contribution to vulnerability to tuberculosis [54]. As we have seen, the effects of climate change will adversely affect the availability of nutritious food. The global prevalence of tuberculosis and ongoing transmission in regions at risk of nutritional deficiency makes tuberculosis concerning as a pandemic poised to accelerate under these conditions. Tuberculosis is also a disease that thrives in the aftermath of extreme weather events and natural disasters, as crowding, poor housing and weak health infrastructure create the 'conditions of poverty' that enables tuberculosis to flourish [134–137]. Climate and conflict-mediated migration provide an important vehicle for acceleration of tuberculosis transmission in crowded and stressful migration camps, with vulnerable young children trapped in these settings at greatest risk [138–141]. High-income countries have far to go to improve processes that enable well tolerated refugee entry, and to generally ameliorate poor living conditions and access to quality care for recent migrants, even in settings where tuberculosis programs are strong [142,143].

A CALL FOR INTERGENERATIONAL EQUITY AND JUSTICE

Human-mediated erosion of our planetary boundaries poses a classic 'wicked' problem, that is, one with many causes that requires collaboration across multiple stakeholders to solve, where those producing most of the harm are often protected from its effects [144]. Those most vulnerable to these deleterious effects tend to be the people least responsible for causing them, in particular, children [145]. Within the medical community, and especially amongst our paediatricians, it is pertinent to reflect: *what ethical role do those who are tasked with protecting children have to play in the promotion of equity and intergenerational justice, considering the medical mandate of 'first do no harm'?*

Visualized in Fig. 2 (adapted with permission from *Williams et al.* [146▪▪]), medical ethics as they apply to the individual (first dimension) are well characterised in the four pillars of beneficence, non-maleficence, respect for autonomy and justice. The 'prosocial' application of medical ethics to the collective (second dimension) underlies public health and is critical to ensure clinical practice aligns with distributive justice, value for money, 'greatest good for the greatest number', altruism, solidarity and reciprocity [145,147,148]. However, neither of these dimensions fully encapsulate the obligation current generations have to future generations, as our transgression of planetary boundaries contribute to a world that is increasingly hostile to life as we know it [145]. In our care for the health of today's humans, we must be mindful not to neglect the 'third dimension' of medical ethics, which emphasizes intergenerational equity and justice [146▪▪]. The third dimension of medical ethics would, for example, promote commitments to reduce the use of single-use plastics in healthcare [149], which in the United States alone generates 1.7 million tonnes per year of plastic waste (contributing to our transgression of the novel entities and climate change planetary boundaries) [150]. The third dimension of medical ethics demands that medical professionals become advocates for climate-sensitive practices in their workplaces, without which healthcare services risk complicity in the overconsumption that is endangering our children and their right to healthy futures. As professionals tasked with safeguarding child health, healthcare can no longer be 'apolitical' (if it ever was) when it comes to policies that stand to further marginalize the planetary systems upon which we depend to nourish life [151]. Current estimates indicate that climate change alone is already contributing to significant morbidity and mortality, with up to 131 000 additional child deaths anticipated each year by 2030 if we fail to arrest and restore our deteriorating planetary health [152].

Without an enhanced focus amongst the medical community on prioritizing research and resources towards restoring and protecting the systems that nurture life on earth in its glorious biodiversity, our vulnerable children and future generations will continue to suffer an inequitable burden of infectious disease in the fallout of life beyond safe planetary boundaries [8].

CONCLUSION

At a basic level, children are the most disempowered population in a democratic society, and are completely reliant on adults to consider their best interests. Future generations have no voice and no representation, although they will be heavily impacted by the world that we (adults) are creating, and the environmental legacy of our decisions. Climate change and biodiversity collapse represent the greatest current threat to child health, though this is insufficiently recognised by paediatricians. It is imperative that we mitigate and restore the harms that our transgression of planetary boundaries will wreak upon the health of today's and tomorrow's children. We need to embed generational equity into our ethical frameworks and public health responses. Paediatric medical professionals must 'lead the way' in climate sensitive practices and advocacy, and actively engage with climate science and our planetary obligations to protect children and future generations, or we risk sacrificing the very principles that have always guided medical care and paediatric practice.

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Conflicts of interest

No conflicts of interests to declare.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
- ▪ of special interest
- ▪▪ of outstanding interest

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The current update on the planetary boundaries, including what they are, how many have been transgressed or are on track to be transgressed and the likely implications for life on earth.

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