Research Topics

The relationship between health and environment under the lens of climate change: insights for policy makers

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The relationship between health and environment under the lens of climate change: insights for policy makers

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Editorial: The relationship between health and environment under the lens of climate change: insights for policy makers

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Editorial on the Research Topic
The relationship between health and environment under the lens of climate change: insights for policy makers

Introduction

The temperature of the atmosphere continues to rise as an effect of climate change. According to WMO (World Meteorological Organization) models, there is 80% likelihood that global warming will approach 1.5°C above pre-industrial levels in the next few years, with severe direct and indirect impacts on human health (1). Addressing the climate-health relationship is therefore both highly relevant and urgent. This editorial aims to present a collection of studies that offer a comprehensive perspective on existing and emerging health issues related to climate change, while providing some insights for policymakers to guide future actions.

The effects on human health are manifold, affecting physical, emotional, and psychological wellbeing. Limited to the immediate ones, Hurricane Helene caused at least 130 deaths in the U.S., the flooding of Valencia at least 219, and the 2023 heat wave killed 47,000 people in Europe (in excess of what was expected) (2). These are just a few recent examples limited to rich countries, to which direct and catastrophic effects in Low and Middle Income Countries (LMICs) must be added, plus the indirect effects such as increased risks of infectious diseases and damage to agriculture and food production. Although attributing individual episodes (floods, hurricanes) to climate change is difficult, their sequence and intensity globally indicate that climate change is having a major impact. An international network called World Weather Attribution (WWA), which aims to establish causal links between climate change and catastrophic events, calculated that in the U.S., during Hurricane Helene, the observed precipitation was 70% and winds 150% more likely to occur as a result of climate change (3).

The World Health Organization (WHO) estimates that between 2030 and 2050, climate change could result in an additional 250,000 deaths annually (4) due to malnutrition, malaria, diarrhea, and heat stress, disproportionately affecting poorer nations with limited healthcare resources to tackle emerging environmental challenges. Air quality, closely tied to the climate crisis, represents another major global health risk. Air Pollution, exacerbated by greenhouse gas emissions and climate change, is responsible for ∼6.7 million premature deaths annually (WHO), with vulnerable populations, such as children and older adults, being particularly at risk (5).

The environmental crisis is not only a physical health issue but also profoundly affects mental health. Recent studies show that people are experiencing complex psychological responses, including depression, anxiety, stress, and insomnia (6).

The human, social and economic costs of these phenomena are very high, and in the medium to long term they will outweigh the costs of mitigation, i.e., of reducing greenhouse gas emissions. In the United States alone, the number of disasters costing more than $1 billion each has increased from six in 2002 to 18 in 2022 and 28 in 2023 (7).

The exacerbation of climate change and the need to discuss a strategy for global public health

The problem touches all generations but especially the youngest and future generations, creating severe inter-generational inequality. With each increase in global warming, regional climate changes, even radical ones, become more widespread and pronounced. This is a legacy we leave to future generations.

However, the Research Topic is not only one of inter-generational justice but also intra-generational justice. Although climate change has global coverage, its impacts are not evenly distributed. The effects of rising temperatures, extreme weather events, and biodiversity loss, combined with environmental degradation and increasing pollution, do not affect everyone equally. Those who have contributed the least to creating the problem, such as Indigenous communities, vulnerable populations, and countries in the Global South, are often the ones bearing the most severe consequences, exacerbating disparities in wellbeing and health.

The continuing emergencies we are witnessing therefore highlight the urgency of adequate prevention, given the many casualties, destruction of property and waste of public money. Prevention can be done by acting on the causes (mitigation) and defending populations against the effects (adaptation). As argued by Butler in this Research Topic of Frontiers in Public Health, we need bold new policies if we hope to avoid the collapse of human civilization, addressing both the mitigation and adaptation of climate change's effects on health and wellbeing. These policies must rely on a renewed way of doing science—one that does not shy away from difficult discussions, takes courageous positions, and is grounded in rigorous scientific methods and data.

The obstacles to policy decisions

While discussions on private sector mobilization and global political efforts to implement mitigation measures have been ongoing for years, the recent Emissions Gap Report 2024 by UNEP has documented yet another record high in greenhouse gas emissions: in 2023, emissions reached 57.1 gigatonnes of CO_2 equivalent, marking a 1.3% increase compared to the previous year (8).

Despite the efforts and global awareness, the data reveal a stark gap between the ambitions of the Paris Agreement and concrete action, with emissions continuing to rise globally. The achievement of the Sustainable Development Goals (SDGs) set out in the 2030 Agenda is also lagging behind. Recent analyses indicate slow progress (only in 17% of the overall SDGs), and in some cases, outright regression compared to 2015 levels (9).

Consideration must be given to what are current obstacles to global action: the export of emissions, the failure to help fossil fuel-dependent economies, the weakness of international agreements, and the costs of adaptation and mitigation strategies. The international community has attempted to address these challenges through regulatory and financial mechanisms such as the Loss and Damage funds and the Kunming-Montreal Global Biodiversity Framework. These agreements represent a step toward addressing the environmental crisis equitably and inclusively, by providing technical and financial support to the most vulnerable countries. However, available funding remains woefully insufficient compared to the scale of the needs, with an estimated gap amounting to billions of dollars.

It seems to us that at the moment the public discussion on mitigation stagnates and it is difficult to identify a shared strategy. In this context, we believe health is a central issue. While the discussion on the relationship between health and climate change gained notable attention at COP28 in Dubai, these considerations remain marginal in political discourse, corporate agendas, and public awareness. A fundamental shift in perspective is urgently needed. Health must be brought to the center of the climate conversation. As Kate Raworth reminds us, we cannot speak of a "safe and just operating space" without recognizing the inalienable right to health (10).

The need for strategic and inclusive solutions

One of the main challenges in policy decision-making regarding health consequences of climate change lies in the uncertainty about which solutions are most effective and cost-efficient. In this sense, the calls for grants of the Wellcome Trust and ESRC in the UK, which aim to produce systematic reviews of the scientific literature on mitigation solutions, including taking into account co-benefits and costs, are crucial. A previous, partial attempt has been the Global Calculator, including incorporation of co-benefits for health (11).

While climate is a global phenomenon, its effects and impacts are heavily influenced by individual discriminatory factors, as well as sociocultural, infrastructural, and territorial vulnerabilities. For this reason, policies should: (a) be based on heterogeneous, representative and up-to date data; (b) be tailored to territorial needs rather than standardized; (c) address and combat discriminatory factors and inequalities; (d) fight cognitive biases that perpetuate unfair and unequal treatments.

Therefore, there is an urgent need to develop practical, context-specific solutions. For instance, Kennedy et al. in this Research Topic developed a method based on eco-social approaches to health to implement climate adaptation and mitigation strategies on Cortes Island, a remote area in British Columbia, Canada. Their planning was informed by community-identified needs and preferences, demonstrating the importance of integrated, solution-oriented practices grounded in the real necessities and characteristics of the territory.

A complementary approach is proposed by Katapally and Bhawra, who emphasize the use of citizen-driven big data to address the challenges of climate change. Their approach integrates accurate, timely, and multisectoral data by leveraging the widespread use of digital platforms and devices. Such data can support health systems to predict and prevent global health crises, enabling rapid responses to emerging risks and providing real-time support to citizens.

In this context, it is particularly relevant to adopt non-discriminatory approaches that respect and integrate the cultures of ethnic minorities and Indigenous peoples. These communities maintain a deeply rooted relationship with nature, consolidated within socio-cultural systems that remain intrinsically tied to it for religious, identity, economic, and survival reasons. According to recent estimations (12), in the last 10 years (between 2010 and 2020) forests—upon which roughly one-third of humanity, including many Indigenous communities, directly depends (13)—are disappearing at a rate of 4.7 million hectares per year. This loss not only threatens food and water security but also erodes the cultural identity and stability of communities. Similar challenges confront Aboriginal communities in Australia, where the increasing frequency of natural disasters, such as bushfires, has caused significant destruction. As the resources upon which these populations rely become increasingly endangered by environmental degradation, it is crucial to understand how this affects their livelihoods, psychological wellbeing, and mental health, in order to identify culturally sensitive solutions and political strategies, as suggested by Upward et al..

From a research perspective, it is essential to deepen our understanding of the relationship between external environmental factors and internal homeostasis, by financing researches to study the effects of exposure to physical, chemical, and biological stressors related to climate change on the exposome and the resulting negative health outcomes, as proposed by Robert Barouki.

However, policy makers cannot ignore a major issue in the discussion. Addressing climate change through policy also requires, as Butler highlights, fostering "nuanced, mutually respectful discussions about population and consumption." Saraswati et al. provide essential evidence on the relationships between human population growth, environmental integrity, human prosperity, and climate change. This evidence underscores the risks of environmental degradation and the intensifying effects of climate change as populations grow, which should be considered when planning long-term solutions. These solutions should prioritize ethical family planning, women's empowerment, education, child health, and food security.

While improving data collection and accuracy, and developing tailored solutions to effectively and inclusively address the consequences of climate change, policymakers should also prioritize reducing the ecological footprint of the healthcare sector, a significant contributor to greenhouse gas emissions. Addressing this challenge requires a reimagining of healthcare processes through the adoption of innovative technologies and approaches. Policymakers should promote the application of selection criteria for healthcare procedures that consider environmental impacts alongside patient health priorities. In this context, Sack et al. demonstrated that environmentally-extended input–output analysis (EEIO) can serve as a valuable decision-making tool in the healthcare sector. Their findings suggest that the stenting pathway for stable coronary disease is preferable to coronary surgery from an environmental standpoint, as it significantly reduces the associated carbon footprint. Similarly, Usher et al. highlight the transformative potential of virtual healthcare and health education. Services such as telehealth and virtual education programs, which saw increased use and satisfaction during the COVID-19 pandemic, provide an effective means of reducing emissions associated with in-person care and education delivery. These tools have the potential to play a pivotal role in the transition toward a net carbon-zero future in the health care sector. Clear policy direction is needed to guide healthcare operators in understanding the extent to which such solutions can be applied and in which contexts, ensuring that decisions are not left solely to individual initiative or discretion.

The multiple and multidisciplinary challenges that climate change poses to health demand a paradigm shift in vision, tools, and approaches. As highlighted by Leonardi et al. (a) to successfully support the transition of human societies toward ecological sustainability, it is vital to empower practitioners across all disciplines relevant to public health. Leonardi et al. (b) advocate that supporting and transforming the education and training of current and future generations of practitioners and decision-makers is a crucial step to be implemented, fostering collaboration across countries and disciplines.

In conclusion, this Research Topic sheds light on a theme that, despite being widely discussed in scientific literature, struggles to gain a central place in international negotiations. What is required is a cultural shift, a transformation in perspective and approach—not only from healthcare workers and decision-makers but from society as a whole. The monumental and imminent challenges posed by climate change can only be faced together, through collective commitment, shared responsibility, and decisive action.

Author contributions

GC: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. PV: Conceptualization, Writing – original draft, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Understanding solastalgia from a decolonised, Indigenist lens: a scoping review

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The objective of this review is to use a decolonised, Indigenist lens to understand the definition of solastalgia from an Aboriginal perspective, as a potential emotional response experienced by Aboriginal communities impacted by increasingly frequent natural disasters, such as bushfires. Initial search results revealed a lack of literature referencing solastalgia in an Aboriginal-specific context. Indigenist research methodologies such as Heuristic inquiry and Aboriginal Participatory Action Research (APAR) contributed to the identification of alternative terminologies, which led to the majority of the included publications referring to solastalgia-related concepts, with one included publication mentioning solastalgia specifically. These methods were consequently used to synthesize data, confirm results and contribute to final discussions. Lastly, our results determined that at this stage there is insufficient evidence to conclusively suggest that Aboriginal Peoples in a general sense, experience solastalgia. Acknowledging the ethical dilemma and potential harm of generalising personal philosophies and experiences based on Culture. Thereby, signify the need for further research in this space and in particular, from a decolonised, Indigenist perspective.

Preface: In the context of this review, we as co-authors are mindful of and respect the tensions or politics associated with proclaiming or discussing the identities of Australia's First Peoples. Therefore, in the context of this review, the often preferred term *Aboriginal* refers to the traditional owners of Australia. Where possible, traditional place/tribe names are written to acknowledge the ownership and origins of the information referenced within this review. Furthermore, we wish to acknowledge the storeys and traditional knowledge shared by the authors of the studies referenced within this review. These words of Country and Kin have contributed to the development and conceptualisation of this literature review, and we wish to pay our respects and appreciation.

KEYWORDS
Aboriginal, Australia, solastalgia, Country, resilience

1 Foreword

Aboriginal peoples within Australia have experienced extreme adversity since the dawn of colonial invasion. Since this time, Australia has witnessed rapid industrial growth and widespread development, often resulting in detrimental changes to the environment. The ecosystem has, in many ways and many places, suffered irreversible damage and experienced great biological losses as a result of the environmental disruption (1). Additionally, studies suggest that ecosystems of settled regions have deteriorated as a result of the displacement of Aboriginal Peoples, who traditionally tended to the land (1). Consequently, the impact of disconnection from Country [a term often used by Aboriginal peoples to describe the lands, waterways, and seas to which they are connected (2)] has disrupted and, in some cases, ceased the practise of intergenerational transference of cultural knowledge due to colonial enforcement and influence. Aboriginal Peoples continue to face a long and arduous journey to find and repair the remnants of their history, cultural knowledge, and practises. This disturbance of intergenerational systems of knowledge has had a profound impact on the social, emotional, and physical wellbeing of Aboriginal Peoples (3), thereby contributing to the ongoing experience of intergenerational trauma (4).

As Western development continues to expand and the demand for extractive natural resource industries increases, the disconnection between Country and community grows. Furthermore, extractive practises have been proven to contribute to the exacerbation of climate change effects, thereby inducing the prevalence of weather-induced risks such as extreme fire disasters (5). Studies suggest that climate change-induced weather events and natural disasters have increased the presentation of mental health diseases, such as sleep disorders, stress, anxiety, and depression, and may cause the development of more serious issues such as post-traumatic stress disorder and suicidal ideation (6, 7). According to the United Nations (8), Aboriginal Peoples, in particular, are among the first to face the direct consequences of climate change due to this close relationship with the environment and its resources. The cultural traditions and spirituality of Aboriginal Peoples are strongly connected to maintaining the wellbeing of Country (9), and the decimation of the land brings a profound sense of grief and loss as land is seen as central by many (10). However, this observation is rarely considered, and Indigenous voices are seldom included in national discussions on climate change. During the Native Title Conference of 2008 (11), Warwick Baird stated:

> Climate change was impacting and was going to impact even more on Indigenous Peoples globally in a unique way because of this deep engagement they have with the land... In Australia, climate change policy is developing rapidly and Indigenous People are not included or their engagement is on a piecemeal basis (11).

In 2019/20, the frequency, intensity, and impact of natural disasters due to climate change became all too apparent when the catastrophic disaster dubbed the *Black Summer Bushfires* spread across Australia. This disaster was unexpected and nothing like Australia had ever experienced before (12). Occurring at the end of a severe drought, the bushfires resulted in unprecedented devastation across much of the Country, with estimates suggesting 14.5 million acres of land were affected (13). Bushfires, like other natural disasters, have long-term effects on the mental health of affected individuals and communities (14), and as previously stated, have a profound impact on Aboriginal Peoples. As such, a growing body of research into the psychological impacts of climate change began to evolve, and new developments of language emerged in response to the emotional experiences described by those affected. The use of pre-existing and recently coined terminologies emerging from this space, such as eco-anxiety (15), eco-angst (16), and solastalgia (17), began to appear in the respondent literature. A thorough examination of the development and definitions relating to these emerging terminologies revealed a particularly interesting correlation between the origins of solastalgia and the potential application of this term regarding Aboriginal-specific emotional responses. Subsequently, the term "solastalgia" was chosen as the basis of this review.

In alignment with the aim of this review to apply a decolonised, Indigenist lens, conventional scoping review processes have been adapted or replaced by generally unfamiliar Indigenist methodologies. Additionally, the conventional structure of this review has been modified to read as an *iterative* or *circular* storey.

2 Introduction

The term solastalgia was coined by the environmental philosopher Professor Glenn Albrecht (18). Solastalgia refers to the lived experience of distress caused by the loss of value and the desolation of one's home environment. This conceptual condition manifests in feelings of placelessness and being undermined by forces that destroy the potential for solace in these situations. Furthermore, solastalgia is defined as a form of homesickness experienced when one is still at home yet is affected by the destruction of one's home environment (19). The term solastalgia appears under the umbrella of "Psychoterratic States" (20), which is a concept defined as "the health relationship between the psyche and the biophysical environment" (20). During the term's conception, Albrecht explored the philosophical relationality of psychological states and environmental destruction after he identified the correlation between the prevalence of open-cut mining and drought in eastern Australia and the psychological impact on the surrounding communities (21). This relationality is reflected in the results of preliminary searches of current publications. Additionally, the term solastalgia was found to be discussed primarily in relation to the population as a whole rather than in the context of specific populations. Evidence of this finding was reflected in the resulting scoping reviews identified in the preliminary searches. The three scoping reviews identified presented little discussion of Aboriginal-specific content, thus contributing to the hypothesis that solastalgia has not often been discussed in the context of an Aboriginal perspective.

There was, however, one scoping review that showed potential. It was conducted with the aim of mapping the existing literature on solastalgia within an Australian context with a particular focus on Aboriginal and Torres Strait Islander experiences (22). Consequently, one of the key outcomes of the review was the recommendation that solastalgia should be further explored in the context of Aboriginal and Torres Strait Islander perspectives as a result of identifying the possibility of Aboriginal Peoples being particularly at risk of experiencing solastalgia. Additionally, the review recommends further exploration of the suitability of applying the term solastalgia to Aboriginal and Torres Strait Islander Peoples' emotional responses/experiences to environmental change (22). Furthermore, the review provided support for this current review by stating that future research into solastalgia would benefit from being conducted using a decolonised lens (22).

As corroborated by the results provided by Breth-Petersen et al. (22), an extensive search of the Pubmed, ProQuest, INFORMIT Indigenous, EBSCO, and Google Scholar databases determined that there was a significant gap in the literature that failed to include Aboriginal-specific discussion relating to solastalgia. Additionally, those in existence were primarily authored by non-Indigenous academics and were not reflective of a decolonised lens.

Given the importance of "place" and Country in Aboriginal cultures, the suggestion of further research into an Aboriginal perspective of solastalgia, and the recommendation of a decolonised review, we proposed that place-based lived experience of solastalgia in Aboriginal Communities should be a key aspect identified within the chosen publications of this review. Therefore, this study aims to provide a comprehensive scoping literature review of the concept of solastalgia from the perspective of Aboriginal Peoples' experience of the phenomenon whilst embedding a decolonised, Indigenist approach. Additionally, this literature review was conducted during the initial stages of the lead authors' (known hereafter as KLU) PhD project as a way of examining the scope of current solastalgia-related literature in the context of applying the concept to Aboriginal Peoples' experiences of negative environmental change. Before conducting this review, KLU developed an Indigenist understanding of the term by performing a modified heuristic inquiry study (23) (see Data Sheet 1).

3 Review questions

The objective of this review is to contribute to the narrative of decolonising discussions within the realms of Aboriginal experiences of climate change and explore the potential application of the term solastalgia to the experiences of Aboriginal Peoples. Research on decolonising practises suggests that co-researching methodologies should be included in designing and conducting research. This practise aspires to re-cover, re-cognise, re-create, re-present, and "re-search back" using Indigenous ontological and epistemological constructs (21). Therefore, with respect to embracing co-design, also known as Aboriginal participatory action research (APAR) (24), a discussion was held with the University of New England's (UNE) Aboriginal Advisory Committee, which consists of local Gamilaraay community members, facilitated by the stakeholders of the UNE Medical Research Futures Fund (MRFF) bushfire impact study. The community consultation resulted in a unanimous agreement that the preceding literature review should be conducted in a decolonised manner, applying an Indigenist lens, and include publications that focus on an Aboriginal connexion to the Country.

The questions that guide this review were collaboratively developed by the UNE Aboriginal Advisory Committee, authors, and academic associates of the research team who identify as Aboriginal or have extensive professional experience in Aboriginal mental health research.

The aim of this review is to:

- Apply a decolonised, Indigenist lens in the identification of publications, analysis methodologies, and resulting discussions;
- Explore the value of Aboriginal authorship, collaboration, and community participatory research methods in Aboriginal-specific climate change discussions;
- Map/outline how the concept of solastalgia as experienced by Aboriginal Peoples is revealed in the literature; and
- Examine the relationality of connexion to Country or place and solastalgia.

The following research questions guide the review:

1. How do Aboriginal peoples experience solastalgia?
2. Are there similar concepts of solastalgia discussed within Aboriginal-specific literature relating to the impact of environmental change?
3. What can we learn from the literature in terms of the distress associated with environmental change?

4 Eligibility criteria

4.1 Concept

The typical process of conducting a Higher Degree of Research (HDR) project requires the candidate to explore their chosen topic by conducting a literature review. The aim of the literature review process is to "map rapidly the key concepts underpinning a research area and the main sources and types of evidence available" (25). However, as evidenced by the initial searches conducted at the beginning of this literature review, published literature discussing solastalgia from an Indigenist perspective is few and far between. Therefore, the researchers conducting this literature review conceded that a conventional Western review process would be inappropriate. They were particularly pertaining to applying a decolonised, Indigenist lens.

Further examination of Indigenist methodologies suggests that autonomous perspectives derived from lived experience, cultural backgrounds, and prior cultural teachings are essential elements of postcolonial scholarship. As defined by Tsinnajinnie et al. (26), Indigenous research is "An intentional decolonisation process that we engage in as Indigenous individuals with many shared values linking our spaces together, inserting Native epistemologies, and honouring the reclamation of how and why we seek knowledge" (26). Consequently, unlike the usual process of conducting a literature review, the Indigenous researchers on this project convened in a series of virtual "yarning circles" to discuss the concept of solastalgia from a lived experience, Indigenist perspective and determining the best course of action for this review. These discussions were led by KLU, who had spent a period of time delving into the conceptual elements of solastalgia using heuristic inquiry, thereby beginning the scoping review process with a pre-conceived notion of how the term solastalgia may or may not reflect the deep sense of homesickness and loss related to environmental change as experienced by Aboriginal Peoples. Additionally, as posed by the team and later confirmed by Professor Albrecht himself, in an unpublished conversation with

TABLE 1 Inclusion and exclusion criteria for literature review screening.

Inclusion	Exclusion
• Peer-reviewed and/or grey literature, provided it demonstrates discussions that align with the concepts asked within the key questions; • Literature featuring discussions of the relationship between Country and a sense of loss as a result of environmental changes; • Aboriginal-specific literature, with discussions of Aboriginal perspectives or experiences; • Literature that includes discussions about the importance of Connexion to Country as an imperative element of Aboriginal cultural ties, kinship, and place-based positioning.	• Literature without a particular focus on discussions involving the experiences and perspectives of Aboriginal peoples; • Literature derived outside of an Australian experience; • Secondary literature; • Non-human related research; • Grey literature is found to have had no level of the peer-review process.

KLU in 2023, solastalgia is defined as an emotional response related specifically to the degradation of the biophysical environment. Biophysical means "involving biological or physical factors or considerations" (27), thereby limiting the potential of extending the term solastalgia to broader causes such as psychosocial factors that are inherently interconnected, for instance, the spiritual dimensions of an Aboriginal Persons relationship to Country.

Therefore, due to the possibility of alternative perspectives of the same concept, resulting in the potential of differing language, this review developed into a systematic process of inquiry designed to explore the basic underlying concept of the term.

4.2 Context

The context of this review is to examine the current existing published literature to form the basis of a Ph.D. project that will explore the experience of natural disasters, such as bushfires, by Aboriginal peoples. By developing an understanding of the possible emotional responses related to detrimental environmental changes. In particular, the application of the term solastalgia in consecutive publications.

4.3 Types of sources

As stated previously, the answers we seek are not embedded in Western philosophy or methodologies alone. They require an atypical, decolonised, Indigenist approach to draw out the information.

Throughout the numerous "yarning circles" held, the authors devised a list of appropriate inclusion and exclusion criteria to guide the literature selection process (see Table 1). Additionally, the authors considered both qualitative and quantitative studies, perspectives papers, and both peer-reviewed and grey literature. However, grey literature would only be included within this scoping review if it was determined to be from a reputable source.

5 Methodologies and framework

No specific framework was initially developed to carry out the process of this review. Instead, this review retained a fluid and "living" working practise, developing autonomously with guidance from both Western and Indigenist methodologies. See Data Sheet 1 for an extensive Methodologies and Frameworks list and summary.

The resulting process was conducted as follows:

A decolonised, Indigenist Scoping Review Process

1. KLU dedicated 6 months to thoroughly understand the concept of solastalgia by conducting a period of modified, creative, Indigenist heuristic inquiry (23). Throughout this, numerous conversations were held with esteemed elders, Gamilaraay community members, climate change impact experts, and the researchers involved in conducting the scoping review. During this time, three paintings were created as a way of conceptualising, visualising, and translating gained knowledge;
2. The researchers conceded that in addition to the guidance of "Quandamooka" by Martin and Mirraboopa (28), the Joanna Briggs Institute methodology for scoping reviews (29) would be consulted in the literature review design. This guideline informed the review process and the structure of the final report. Additionally, the PRISMA-ScR reporting guidelines (30) were chosen to create a modified display of the search results;
3. An *a priori* (29) protocol (unpublished) was developed as a "living" document, thereby changing as the direction, content, and process change;
4. Initial database searches were conducted with the following search terms:
   "(solastalgia OR solistalgia) AND (indig* OR aborig*) AND (kinship OR connexion OR placelessness OR climate change) AND "Australia."
   This search was performed with the assistance of the UNE librarian and produced inadequate results;
5. The heuristic inquiry process led KLU to deduce that publications relating to similar concepts defined by the term solastalgia may be present; however, the language used may vary due to the potential deviation from contemporary Western nuances. To further explore the concept of solastalgia and determine the appropriate means of conducting this review, the researchers convened with the UNE Aboriginal Advisory Committee in an informal "yarn." Committee members were provided with an in-depth explanation of the term solastalgia and were asked to "*yarn-up*" (discuss) their understanding of the word whilst allowing space for questions and debate. It was determined that the Aboriginal philosophy of connexion to Country may result in a greater sense of loss associated with environmental change. Additionally, the elders suggested that the experience of environmental change may indeed impact Aboriginal peoples emotionally, and also physically and spiritually, and result in widespread changes in community dynamics, alongside a disconnection from the Country. Additionally, this meeting assisted in determining the appropriate search terms for the second search and the inclusion/exclusion criteria for the chosen literature;
6. Individual "yarns" were had between KLU and the Aboriginal members of the research team, thus determining the methodologies that would inform the review process, confirming the appropriate research questions, and validating the search terms;
7. Researchers KLU, RS, and JD met virtually to conduct the database search. Before beginning the search, the researchers

TABLE 2 PAGER framework table.

Pattern	Advances	Gaps	Evidence	Research recommendations
Authorship of Country and traditional knowledge	- Authorship of Country - Collaborative research methodologies such as Aboriginal Participatory Action Research (APAR). - Increasing frequencies of Aboriginal and Torres Strait Islander researchers, contributing to Aboriginal-specific research. - Where research involving Indigenous fields of study are conducted by non-Indigenous researchers, co-design methods or consulting is used.	- Database search identified four texts, currently published, featuring Country as lead author. - Traditional knowledge's infrequently cited by the following selected publications, "Strange Changes," "We're the same as the Inuit," "Future sea changes," and "Solatalgia and the Gendered Nature."	- Current published works featuring Country as the origin of knowledge.	- Prime examples of Country authorship will encourage the development of future literature to adopt a similar approach. - It is recommended that a continued effort is required to involve Aboriginal researchers in Aboriginal-specific research. - Utilising Indigenist research methodologies. - APAR methods of co-design.
Storytelling as methodology	- The adoption of storytelling methodologies present throughout most of the selected publications. - Storey utilised as a translation methodology	- The publications that featured "western" methods of data collection, selected relevant, but fractured samples of text, rather than featuring the storey in it's entirely. This, potentially misrepresenting the context.	- Each of the publications featuring Bawaka Country as lead author, succeeded in interpreting Traditional systems of knowledge in a comprehensive yet accessible manner	- Indigenous Data Sovereignty recommends that storeys should be featured in their entirety
Terminology	- Proven theory of similar terminologies pertaining to climate change are present in all chosen texts, whilst demonstrating that some terminologies may differ, depending on the context or Country of origin.	- Database searches using direct terminologies used in climate research context did not produce extensive results.	- By broadening the search terms to suit Indigenist research, a wider body of work was discovered.	- Future Aboriginal-specific climate change research, should feature broad terminologies, as well as climate-specific terms. Thus, allowing them to be more easily discoverable.
Aboriginal perspectives and experience of environmental change	- The selected publications that discuss environmental change, specifically, features elements of Aboriginal perspectives from direct sources.	- "Aboriginal" perspectives are a generalised term, and does not allow for alternative perspectives derived from factors such as, Country of origin.	- Four texts depict environmental change as distressing. - The remaining texts conceptualise climate change alternatively.	- Further research should explore the alternative perspectives, Cultural knowledge's, philosophies and ontologies of a broad range of Aboriginal peoples/communities.
Connexion to Country and environmental changes	- The relationship of connexion to Country, discussed extensively throughout the texts. - The impact of environmental change effecting this relationship is explored throughout the texts.	- There discussions feature within the texts, that do not explore the connexion between "grief and loss," pertaining to a connexion to Country.	- Each of the texts feature discussions of environmental change being observed by Aboriginal peoples.	- It is recommended that future research of Climate Change that discusses the impact on Aboriginal peoples, should feature the impact of relationships to Country.
Adapting to environmental change	- Depictions of resilient attitudes towards the future, were evident throughout each of the texts. - Climate change adaption discussions and planning were evident throughout most of the texts.	- The literature rarely identified currently implemented and successful adaption practises.	- Most of the texts suggest immediate adaption conversations between community and key change makers i.e., policy writers	- Further research is recommended to explore potential adaption strategies.

discussed, in detail, the pre-determined concepts within solastalgia and the inclusion/exclusion criteria. JD performed the searches whilst screen sharing with the other researchers. The results were extracted and loaded into EndNote (31) software. Duplicates were removed, deductions were made via title search and year, deductions via abstract content, and finally, full-text skimming produced a total of 35 publications (see Section 6; search strategy);

8. Each of the researchers read the publications independently. A secondary virtual meeting was held in which each of the researchers produced their chosen literature. A lengthy discussion took place about the appropriate direction for the review and accompanying texts. Finally, six of the publications were chosen for the scoping review;
9. KLU uploaded each of the six publications into NVIVO (3) software and used the software function of determining the "most common words" (see Data Sheet 2). Additionally, a data extraction table (see Data Sheet 3) was collated, thereby informing the process of determining the recurring themes within the texts, which were further examined and correlated using a PAGER Framework (32) table (see Table 2);

10. Researchers KLU, RS, and JD conducted a final virtual meeting to discuss the extracted data and resulting identified themes. Each of the researchers was in agreeance with the themes, and the results were forwarded to the project team;
11. KLU consulted with two cultural mentors during this time to verify the direction of the review. KLU corresponded with the research team via email with updated versions of the report for validation, feedback, and input. KLU continued to perform heuristic inquiry, discuss solastalgia widely, and revisit the search terms for updated publications. Subsequently, a publication by McNamara and Westoby (33) was discovered, and despite the inclusion criteria stating that texts should reflect Aboriginal perspectives, the text was deemed to be relevant as it discussed Torres Strait Islander experiences of solastalgia. Thereby, the content was analysed and subsequently added to the review. Additionally, the literature review by Breth-Petersen et al. (22) was identified and included in this final report as validation for conducting a decolonised, Indigenist scoping review process.

6 Search strategy

A strategic scoping review protocol had been initially developed as a fluid, living document. Therefore, the process of conducting this review was informed by the discoveries, epiphanies, and insights gained at the time of its development.

As per the recommended scoping review guidelines outlined within the Joanna Briggs Institute methodology for scoping reviews (29), an initial search of the literature was conducted with the assistance of the UNE librarian. The initial search terms (see Section 5; methodologies and frameworks) produced minimal appropriate results. However, this was to be expected. As substantiated by Martin and Mirraboopa (28), the initial search would inevitably produce "sources produced by people and by other entities in the context of Country." Additionally, Martin and Mirraboopa (28) recommend that "Primary and secondary sources by non-Aboriginal people should also be reviewed, keeping in mind the cultural assumptions, standpoints and biases of the author." Furthermore, the use of the term "solastalgia" in the literature pertaining to an Aboriginal experience is uncommon, as confirmed by the subsequently identified literature review by Breth-Petersen et al. (22).

Consultations with Aboriginal community members and the research team resulted in the selected search terms outlined in Section 5 (methodologies and frameworks).

These terms were deemed to be culturally appropriate and reflected the notion of connexion to Country as an important factor of understanding the emotional responses of Aboriginal Peoples as derived from environmental degradation.

As stated in Section 5 (methodologies and framework), a revised search was conducted by KLU, RS, and JD, using the new search terms in the following databases: PubMed, ProQuest, INFORMIT Indigenous, and Google Scholar. The initial results identified 688 citations, after which a screening process was conducted. A title search deducted a portion of the results, followed by a reduction process that kept texts adhering to the following criteria: Date ranged between 2005 and 2022, geographical location restricted to Australia, peer-reviewed texts, and language limited to English. This reduced the search results to 38 citations identified from the databases listed and a further 109 citations identified from Google Scholar. Additionally, three texts were identified through citation searches. Finally, a screening process was conducted whereby duplicates were removed, and the remaining citations were further screened for relevancy, reducing the total to 129.

Each of the remaining citations and abstracts was screened to determine the relevance to the inclusion criteria (see Table 1). A total of 35 texts remained for full-text screening, conducted independently by KLU, RS, and JD. It should be noted that two of the academics involved in the screening process identify as Gamilaraay.

A subsequent virtual meeting was held, whereby KLU, RS, and JD presented their chosen texts and outlined their reasoning. A discussion concluded that the six remaining texts adhered to the inclusion criteria. Additionally, the texts chosen discussed topics and were structured in a way that fulfilled our prior queries, specifically discussions of connexion to Country, Aboriginal perspectives, climate change and/or environmental changes, Aboriginal philosophy, and instances of co-creation. The search process and results are presented using the following PRISMA Flow Diagram (30) model (Figure 1):

During the synthesis of the review, KLU continued to revisit the database search results to identify potentially relevant publications. Consequently, the literature review by Breth-Petersen et al. (22) was identified during a subsequent search, which was determined to be a valuable contribution to the subject matter. However, due to the nature of the inclusion criteria, this publication was excluded from the review, although relevant information within this publication was considered. Additionally, a second publication was identified post-analysis, which primarily featured Torres Strait Islander experiences and perspectives. Regardless of the inclusion criteria, due to the relevancy of the content aligning with the research questions, this publication was included for review. In conclusion, the following seven publications were identified for discussion:

- Petheram et al. (34), "Strange changes:" Indigenous perspectives of climate change and adaptation in NE Arnhem Land (Australia);
- Bawaka Country et al. (35), Gathering of the Clouds: Attending to Indigenous understandings of time and climate through songspirals;
- Nash et al. (36), We're the same as the Inuit!: Exploring Australian Aboriginal perceptions of climate change in a multidisciplinary mixed methods study;
- Petheram et al. (37), Future sea changes: Indigenous women's preferences for adaptation to climate change on South Goulburn Island, Northern Territory (Australia);
- Bawaka et al. (38), Co-becoming Bawaka: Towards a relational understanding of place/space;
- Bawaka et al. (39), Caring as Country: Towards an ontology of co-becoming in natural resource management; and

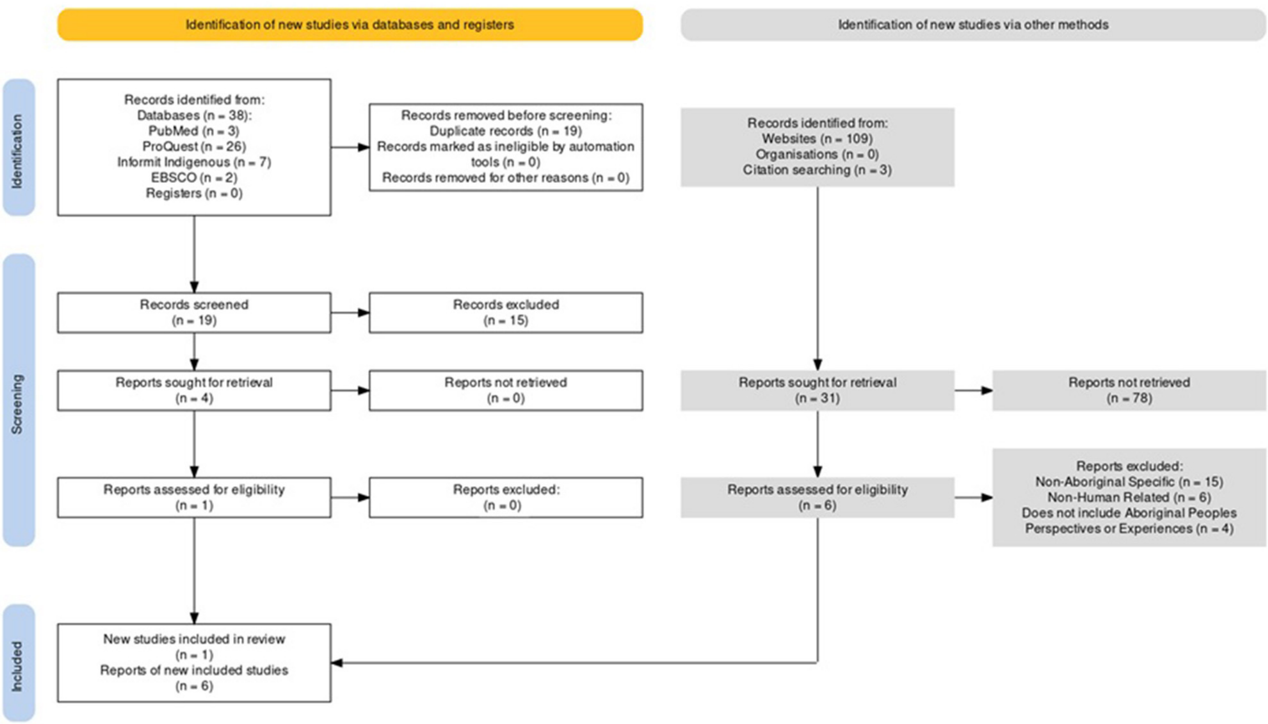

FIGURE 1
PRISMA flow diagram.

- McNamara and Westoby (33), Solastalgia and the Gendered Nature of Climate Change: An Example from Erub Island, Torres Strait.

Seeing as though five of the seven texts feature recurring lead author identifiers, throughout the discussion of this review, the publications will be referred to by the key features of the title, i.e., Petheram et al. (37) will be referred to as "Future sea changes" to simplify readability.

7 Data extraction and analysis

As stated in Section 5 (methodologies and framework), KLU used EndNote (31) software to determine the "most common words" within the combined texts (see Data Sheet 2). The most notable and frequent words with their accompanied derivatives were:

- Changing etc.;
- Climatic etc.;
- Humans etc.;
- Community etc.;
- Country etc.;
- Becoming etc.;
- Indigenous;
- Adaptive etc.;
- Relations etc.;
- Time etc.; and
- Understandings.

By identifying the most common words, themes begin to emerge. Additionally, each of the seven texts was thoroughly examined, the analysis of which informed the development of a glossary of key terms (see Table 3). Key terms were selected by reviewing the "most common words" table (Data Sheet 2), combined with the results of the database search terms and a reflection of previous discussions. Finally, full-text screening resulted in the research team identifying "topics of interest." Key publication information and the "topics of interest" headings were incorporated into a data extraction table (Data Sheet 3), as listed here:

- Author, year of publication, and Country;
- Aim/purpose;
- Methodology/methods;
- Key findings;
- Connexion to Country;
- Knowledge translation/traditional knowledge and practises;
- Climate change; and
- Adaption.

The final column was reserved for recording emerging themes or patterns, as identified through performing a virtual "yarn-up" by the research team. Additionally, whilst discussing the findings of the data extraction table and revisiting the original research questions for this review, the research team compiled the emerging themes into a PAGER framework (32) table.

TABLE 3 Glossary and context of key terms.

Term	General context
Country	Often used to describe the land and all that it encompasses, usually in reference to ancestral lands. Also known as "land" and "place."
Connexion to Country	The spiritual, physical, cultural, social connexion to "Country." This encompasses language, Lore, Kinship and Ceremony.
Adaption	The process of adapting to the changing environment.
Land	The ecosystem that sustainably supports a person or community.
Place	Also known as "home" and "Country." Often used to describe a specific area and the connexions associated.
Placelessness	Often used to describe a sense of disconnection to Country, community and culture.
Kinship	The complex relationship with family, community and Country.
Co-becoming	The interconnected relationship to all things.
Loss and grief	The painful feelings associated with spiritual, physical, social and emotional disconnection from community, Culture and Country.

This framework is a method of identifying the gaps between the key findings of the data analysis and the possibility of answering the research questions. The PAGER framework (32) matrix is typically used as a method of charting "patterns" or identified themes, "advances," i.e., significant discoveries, "gaps" identified within the literature, "evidence," i.e., for practise, and "research" recommendations. The identified themes were compiled into the "pattern" column of the table, and the proceeding information was extracted from an additional revision of the included publications, followed by an informal meeting of the research team, whereby the researchers were in agreement with the resulting information recorded into the following table.

The extracted information presented within the PAGER table informed the subsequent discussion. Furthermore, the table provided valuable insights that were included in the final recommendations of this review.

8 Discussion

8.1 Authorship of Country and inclusion of traditional knowledge

8.1.1 Significance to the review

The selection criteria specifically state that eligible articles will feature Aboriginal perspectives or experiences, with discussions of connexion to the Country as an imperative element. The act of attributing Country with authorship, demonstrated reliability of the information included within the paper by evidencing the original source.

8.1.2 Evidence

To align with the value of cultural responsiveness in Aboriginal research, where possible, researchers should adopt co-design methodologies. The inclusion of Aboriginal peoples as co-researchers encourages Aboriginal Peoples to be empowered and self-determinant and allows communities to control their data, i.e., storeys, cultural knowledge, and art (24). Additionally, colonial influences perpetuated by Western academia can result in disinformation and misrepresentation of ideologies and lead to harmful deficit discourse narratives. Dudgeon et al. (24) illustrated that "The grand narratives of colonial nation states have served as mechanisms to perpetuate a false narrative about a vast and unclaimed territory 'terra nullius' which has fuelled and sustained an epistemic erasure of the trauma, destruction and oppression being imposed on and experienced by Indigenous peoples globally and in Australia." Therefore, by adopting co-design practises, interpretation of results and research dissemination will have greater accuracy and reflect a better understanding of the topic. In recent times, researchers have begun adapting Western research methods to be more inclusive, culturally sensitive, and responsible. As conceded by the article "Strange changes" (34), "The importance of respect for Indigenous views and their incorporation in development planning was emphasised by research participants." Similarly, "We're the same as the Inuit" (29) states that "Indigenous community involvement was integral from the planning stages through to the data collection, analysis and dissemination of results." This practise is essential to improving current Aboriginal-specific research standards, and due to this importance, this factor was included in the considerations of the publications identified for review.

An excellent example of a collaborative design that led to informative and accurate reflections on Aboriginal ways of "knowing, being, and doing" (21), is the paper titled "Co-becoming Bawaka: Towards a relational understanding of place/space" (38). Not only does the authorship acknowledge Country as the lead author and creator of the knowledge origins, but the authors describe the inherent relationship. Furthermore, the study describes the non-Indigenous research partners as being "adopted" into the family of the traditional owners of Gumatj (including Bawaka) Country (38), thereby permitting the non-Indigenous authors to learn from Country and discuss shared knowledge through the teachings passed on by the Gumatj elders. The non-Indigenous authors stated that "Bawaka enabled our learning, our meeting, the storeys that guide us, the connexions we discuss and has, indeed, brought us into being, as we are, and continue to co-become, today" (38). Similarly, reflected in the sentiments of "Caring as Country" (39):

> Acknowledging the authorship of Bawaka Country is important as it decentres the privileging of human authors as the only beings able to control and create, as the sole deciders of content and structure, and opens up opportunities for reimaging and co-creating not only how we write about NRM (natural resource management) but how we think about and practise it (39).

Acknowledging the Country as the origin of traditional knowledge is a responsibility of both Aboriginal Peoples and those who are gifted the knowledge. This element is important to acknowledge and respect the continued practise of caring for Country and acknowledging ontologies that believe in a co-becoming with Country. Additionally, the act of acknowledging and recognising the origins of knowledge demonstrated respect for the non-linear, spoken, and unspoken connexion of all to the Country. Furthermore, accurate representation and ethical use of Indigenous knowledge's pertain to valuing the rights of Indigenous Peoples. The right to determine the use and publication of Indigenous knowledge is recognised as "Indigenous Data Sovereignty" (40), described by Kukutai and Taylor (40), as "the inherent and inalienable rights and interests of Indigenous Peoples relating to the collection, ownership and application of data about their people, lifeways and territories."

For example, the study "Future sea changes" (37) concludes that "Findings of this research suggest that in engaging with Indigenous communities on planning for adaptation, it will be essential to discuss climate change and adaptation in ways that acknowledge differences in knowledge systems" (37), thereby reiterating the value of Indigenous knowledge and actively respecting the rights of Aboriginal participants. By valuing Indigenous data sovereignty, researchers actively partake in exercising decolonising practises.

8.2 Storytelling as methodology

8.2.1 Significance to the review

Storey is a standard facet of data collected within Indigenous research studies. Similarly, storey is a commonly used Indigenous research methodology. The inclusion of storey substantiates the Aboriginal participation within the study and/or paper.

8.2.2 Evidence

Storey was identified as one of the recurrent themes throughout the seven texts. "Caring as Country," (39) "Co-becoming Bawaka," (38) and "Gathering of the clouds," (35) each use *storey* published in their entirety as a method of conveying Yolŋu (Aboriginal peoples of northeast Arnhem Land) ontological philosophies and knowledge. Similarly, "We're the same as the Inuit," (29) "Future sea changes," (37) "Strange Changes," (34) and "Solastlagia and the Gendered Nature" (33), feature storey; however, they include fractured interview excerpts rather than whole interview transcriptions, which consequently may lead to the misrepresentation of information and context. Kovach (41) states that "storeys hold within them knowledge's, while simultaneously signifying relationships." Martin and Marriboopa states (28) that "Storeys are vessels for passing along teachings, medicines, and practises that can assist members of the collective." Therefore, selective information could misinterpret or devalue the information, and interconnexions of the storey may be missed. Interestingly, it calls to question the accuracy of the information represented within a literature review, given that the undertaking of a review is influenced by a systematic bias.

As previously stated, respecting Indigenous Data Sovereignty means valuing the rights of traditional knowledge; therefore, Indigenist research methodologies, such as APAR, allow Aboriginal Peoples to control the use and dissemination of their "data." The practise of extracting key features from a storey is rarely supported by Indigenous researchers as "storeys can never be decontextualised from the teller" (28). Furthermore, Aboriginal storey is irrevocably Indigenous knowledge as derived from the Country. By positioning the storey within its Country of origin, one respectfully acknowledges the unique characteristics, culture, and traditions of that Country. For example, "Gathering of the clouds" (35) tells a storey of the *Wukun* (gathering of the clouds) songspiral, which is unique to Bawaka Country. "Solastalgia and the Gendered Nature" (33), acknowledges that the storeys included in their studies originate from Erub Island of the Torres Strait.

The way in which the storey is documented or translated may lead to differing conclusions. The storey of *Wukun* (35) comes directly from the Country/community and describes a traditional knowledge system. *Wukun* (35) anticipates the ebbs and flows of weather patterns by situating oneself within that system, as part of that system. Acknowledging that in Yolŋu ontology, distressing environmental circumstances will eventually be satiated, "And through the tears of the rain, grief may be stilled" (35). Whereas a mixed method, "Western" structured study, such as "We're the same as the Inuit" (29), identifies unabated distress over environmental change, stating that "It would also appear that deep connexion to and identification with the 'natural' environment understandably increases not only concern and distress with respect to impending and dramatic climate change, but also collective self-efficacy and resolve" (29). This may be an example of storey translated directly from Country, differing from systematic, structured processes, resulting in conflicting sentiments. Otherwise, it may just be an example of alternate perspectives of environmental change. For example, the term "Indigenous" is a common term used to describe the Indigenous Peoples of Australia; however, depending on the preference and perspectives of the referred parties or context of the terms used, "First Nations Peoples" may be preferred. However, it is widely accepted that when appropriate, the specific nation of the referred party should be alternatively used, thus demonstrating the inability to group the preferences and perspectives of *all* Aboriginal Peoples and highlighting the need to explicitly detail the origins of the illustrated perspectives. In acknowledging this fact, we then pose the question, is there truly a way to determine the appropriate use of the term solastalgia as an emotional response experienced by Aboriginal Peoples in a generalised context?

8.3 Terminology

8.3.1 Significance to the review

It was hypothesised that a wealth of literature pertaining to the grief and loss associated with environmental change might be difficult to locate due to the use of alternative language. Therefore, a thorough examination of the language present within the chosen articles was warranted.

8.3.2 Evidence

It was hypothesised that change discussions might typically be disseminated in "English," which may impact translatability, therefore limiting the number of results in the database searches of this review based on this factor. Consequently, an analysis of significant "most common words" was conducted, as contextualised and understood throughout each of the seven publications. The results of which are presented in the following glossary.

The general context of each key term, as described in this glossary, indicates that although the term solastalgia only appears in the text "Solastalgia and the Gendered Nature" (33), the correlating words and context of the terms that are often associated with the concept of solastalgia, are frequently exhibited in the remaining texts, thereby illustrating that language/terminology barriers may inhibit search results.

The definition of solastalgia, as previously discussed, is bounded in the context of the "biophysical" environment. This is a point of connexion among academics, mainstream media, and the general public, all of whom have differing interpretations of the term, thereby calling into question the context in which solastalgia is used.

One participant of the study "Solastalgia and the Gendered Nature" (33), which explores the experience of solastalgia, reflects upon their interpretative artworks by stating that she felt "great sadness as she sensed that her identity was changing" as a result of experiencing changes in her home environment. A factor that is associated with solastalgia, as evidenced by Albrecht (17), states that the experience of solastalgia may lead to "the erosion of the sense of belonging (identity) to a particular place" (17, 33). However, the notion of solastalgia being purely a response to the biophysical environment is explored by the researchers stating, "interviews explored not only the biophysical impacts of environmental and climate change but also potential emotional, Cultural and psycho-social impacts" (33); thus questioning the participant's sentiments as being a response to the biophysical environment, as it may in fact be evoked by factors such a deep connexion to Country. However, the study fails to include substantial details within this context, thereby highlighting the importance of including full transcripts to corroborate the context of the information. Additional details may have provided terminologies that would have given evidence to determine the source of the notion that their "identity was changing" (33).

In the study "Future Sea Changes" (37), participants involved were unfamiliar with the term "climate change." Many of them stated that English was not their primary language. It was identified within the study that participants had a "limited understanding of western concepts and English language terms" (37), specifically "associated with climate change and why change was occurring" (37), demonstrating the importance of language and translatability. Similarly, the study "Strange changes" (34) noted that "Although all participants were familiar with the term climate change and had many ideas relating to its occurrence and potential changes, it became evident that many were unclear about western notions of the concept." Furthermore, "Strange Changes" (34) stated that most participants "said they had heard of the term 'climate change' through media, mostly television;" however, two participants appeared to distance the concept from their own personal experiences of changes within their home environment by associating their understanding of climate change with "Polar caps melting, affecting polar bears" (34). This highlights that societal and personal factors may influence the ability to translate Western terminologies into familiar language and contexts.

Alternatively, the publication "Co-becoming Bawaka" (38) offers a different scenario. Throughout the study, the term "climate change" is frequently used, and its context is understood. "Co-becoming Bawaka" (38) repeatedly relates "climate change" to Yolŋu ontologies. As evidenced by the statement:

> While climate change may appear as a quintessential "unbounded" phenomenon, gurrutu (a complex Yolŋu kinship system immersed in the practise of digging ganguri or yams) will tell us that it is only ever manifested in grounded ways, such as cyclones, storm surges, government reports and protest marches, that are themselves linked to enduring place-based patterns of kinship and responsibility (38).

Consequently, it confirms that Yolŋu Peoples are familiar with the concept of climate change by describing the relationality of the term to complex cultural ontological philosophies and knowledge systems, thereby reiterating the possibility that the participants of the "Strange changes" (34) study may in fact be familiar with the phenomenon of climate change. However, their interpretations of the concept may be embedded in traditional language and cultural knowledge rather than English.

8.4 Aboriginal perspectives or experience of environmental change

8.4.1 Significance to the review

The inclusion criteria states that eligible studies would include Aboriginal perspectives or experiences. Whilst discussions featuring the relationship between Country and a sense of loss as a result of environmental change would be preferable, this review considered a general discussion of environmental change as appropriate.

8.4.2 Evidence

As previously discussed, co-research methodologies such as APAR (24) are an essential component of determining Aboriginal perspectives. If we are to begin practising research that positions the Country as the origin of Traditional knowledge, the following discussions of "Aboriginal perspectives or experience of environmental change" will reflect this sentiment as an example of "best practise."

Storeys derived from Bawaka Country, as told by "Caring as Country" (39), "Co-becoming Bawaka" (38), and "Gathering of the Clouds" (35), are centred around Yolŋu ontological philosophies of time, place, and space. They are illustrating the differences between Yolŋu concepts and comprehension abilities and highlighting the limitations imposed by "Western" constructs of conceptual understanding and self-positioning. These storeys are gifted to the reader as a way of educating the public about the alternative perceptions of our current space, particularly with regards to environmental change by guiding the reader to deconstruct their pre-conceived ideologies and ontologies. Interestingly, this particular sentiment may allow us to consider the possibility that the Yolŋu practise of co-becoming Country, weather, and climate systems may reflect that in Yolŋu ontology, acceptance of what was, what is, and what will be could argue the existence of solastalgia within Yolŋu philosophy. As illustrated by "Co-becoming Bawaka" (38), "understanding place/space as co-becoming has the potential to inform discussion around global environmental change as it may 'significantly' expand people's sense of what Earth futures are desirable and achievable." Continued by, "climate change is not abstract—it too is part of a more-than-human co-becoming which is part of 'us' (in the broadest more-than-human understanding of that word) and as such demands response and responsibility" (38).

Alternatively, "We're the same as the Inuit" (29), "Future sea changes" (37), "Strange changes" (34), and "Solastlagia and the Gendered Nature" (33) discuss the emotional responses towards environmental change, whilst featuring language that is concurrent with standard climate change terminology. Each publication does, however, reflect differing perspectives of the individual experiences of their participants towards environmental change, which are mostly reflective of a negative perception.

8.5 Connexion to country and environmental changes

8.5.1 Significance to the review

The inclusion criteria state that connexion to Country is imperative. However, as acknowledged, individuals have unique perspectives and relationships with their environment. Therefore, this detail is generalised to include both Western and Indigenous terminologies and concepts.

8.5.2 Evidence

It is important to note that the act of translating a storey derived from traditional languages into written English is a difficult process, as the Indigenous philosophies of "knowing, being, and doing" (23) that underpin the context of the storey are grounded in complexity, especially when discussing the complexity of Aboriginal philosophies of connecting to Country. Some narratives are exceedingly exceptional at expressing the inexpressible in such a way that allows the reader to comprehend the context and concepts behind the storey. For instance, "Co-becoming Bawaka" (38) interprets the act of digging for *ganguri* (yams) in a way that allows the reader to understand the complexity of Yolŋu systems of knowledge, demonstrating a skill that is infrequently well-executed; a prime example of decolonised, Indigenist methodologies of interpreting and translating the storey. "Strange changes" (34) illustrates the exploration of the concept of "place," using both qualitative and quantitative methodologies. Concluding that:

> All research respondents exhibited strong connexion to place, and sensitivity to natural landscape. They talked of the social, cultural and physical features in their landscape in a multi-layered and interconnected way. Strong emphasis was placed on the importance of maintaining traditional knowledge, values embodied in nature, health of future generations, and the landscape (34).

Similarly, the study "Solastalgia and the Gendered Nature…" (34) considered this intrinsic relationship by affirming that "Country" denotes not only the physical elements of sea and land but also the spiritual and cosmic relationship that Torres Strait Islander Peoples have with the natural environment.

For the most part, the sentiment of connecting to the Country is positively affirmed throughout the seven texts. However, in some cases, this relationship is perceived as being heavily impacted by environmental degradation. For instance, "Strange changes" (34) states that:

> Participants often talked of (a local) mine's negative impacts on the environment, and how this affected them to their core. The study recalls a participant singing a song they composed titled, White man's mine, which proclaims "Yolngu people have so long cherished the land in our culture we love to share, but you are taking it over again, what do we get in return?" (34)

Similarly, "Solastalgia and the Gendered Nature…" (33) claims that environmental changes appear to be "destabilising traditional ways of knowing and reading the landscape, including the predictability of weather, seasons, tides, and plant and animal cycles."

Differing descriptions of personal relationships with Country as potentially being affected by negative environmental changes reaffirms the theory that the experience of what could be perceived as solastalgia is dependent on individual perspectives based on lived experience and personal philosophies.

8.6 Adapting to environmental change

8.6.1 Significance to the review

Research question three asks, "What can we learn from the literature in terms of the distress associated with environmental change?" The theme of adaption to changes within the environment was present and therefore included within the discussion of this review.

8.6.2 Evidence

An objective of the study "We're the same as the Inuit" (29) was to explore what the future holds for remote Aboriginal communities in terms of climate change adaption by developing an understanding of how they perceive the imposing threat of environmental change. There is evidence to suggest that without adequate research into appropriate adaption strategies, these communities will be disproportionately impacted by climate change. A result of this may be the potential of forced relocation from ancestral lands. "We're the same as the Inuit" (29) states that "despite the increasingly grim predictions of change for inland Australia, and the increasingly harsh conditions endured by its residents, many Aboriginal Peoples do not welcome the prospect of moving away from their communities and their countries as an adaptation strategy." Whereas, "Solastalgia and the Gendered Nature…" (33) makes a different argument by stating that, "Torres Strait Islanders have adapted to biophysical changes in the environment for millennia," followed by "Torres Strait Islander Peoples have co-evolved to adapt between the island, sea, nature and their culture." "Solastalgia and the Gendered Nature…" (33) do however pointedly state that "the future of the islands is uncertain and the unpredictability the changing environment may impede attempts to stay connected to their ancestral lands." Thereby, it is noted that even though Torres Strait Islander Peoples over many generations have adapted to environmental change, the current risks posed by climate change on their Islands may exceed previous adaption strategies, highlighting the imperative need for developing region-specific adaption strategies sooner rather than later.

Whilst climate change-associated risks are similarly intensifying across all regions, adaptation strategies are still feasible for remote Aboriginal communities, as opposed to those impacted by rising sea levels. "Strange changes" (34) expresses that the effects of climate change on Aboriginal Peoples causes a "loss of self-esteem, independence and self-sufficiency, loss of traditional knowledge and imposition of other cultures ways and values and loss of culture and dignity through lost contact with natural surroundings" (34). Consequently, participants were asked to create a list of strategies that may improve the adaptive capacity of their communities. One suggestion was that returning to traditional practises "would allow communities to be less dependent on services and maintain culture" (34). Concurrently, "We're the same as the Inuit" (29) states that "nature-connecting activities could be an important integral component in adaptation strategies to enable improved wellbeing for greater resilience to uncertainty under future climate change and food insecurity" (29). Whilst "Solastalgia and the Gendered Nature…" (33) reaffirms this position by stating, "whilst experiences linked to a changing climate can contribute to Solastalgia, communities that resist or adapt to such changes can maintain their sense of place and identity."

9 Conclusion

The aim of this scoping review was to develop an understanding of how Aboriginal Peoples experience solastalgia by using a decolonised, Indigenist lens. When database searches were conducted, "Solastalgia and the Gendered Nature..." (33) was the only study that specifically referred to the term solastalgia. However, given the relatively new emergence of the term solastalgia, it is not surprising that there is little evidence that the term has been used in Aboriginal-specific literature derived from Australia.

"Solastalgia and the Gendered Nature…" (33) describes the experience of solastalgia as a sense of "homesickness," evident in the depiction of declining familiarity with the Country by Aboriginal participants who continue to live on traditional lands. Alternatively, "Co-becoming Bawaka" (38) suggest that climate change is a "quintessential 'unbounded' phenomenon where the Yolŋu ontology of *gurrutu* (digging for yams) will tell us that it is only ever manifested in grounded ways," and that they themselves are "linked to enduring place-based patterns of kinship and responsibility" (38). Therefore, calling into question the applicability of solastalgia as a generalised emotional response by Aboriginal Peoples and arguing that solastalgia is dependent on the individuals perspective.

In conclusion, the decolonised, Indigenist lens with which this scoping review was conducted has identified a correlation between the concept of solastalgia and a sense of disconnection from the Country caused by environmental changes. However, it determined that at this stage, there is inconclusive evidence that Aboriginal Peoples, in general, experience solastalgia. Solastalgia can, however, be perceived as an emotional response experienced by an individual based on their personal philosophy. Therefore, further research in this space is encouraged.

10 Recommendations

It is recommended that researchers continue to explore the impact of climate change-related disasters and environmental change as experienced by Aboriginal Peoples. It is recommended that future research should include co-design methodologies and/or Aboriginal authorship. By acknowledging the relationship/kinship of Country and community, the direct inclusion of Aboriginal Peoples would greatly benefit future research projects in this space. Furthermore, the deep inherent connexion between Aboriginal Peoples and Country reveals a distinct perspective of environmental change and the potential experience of solastalgia.

The discovery of literature authored by Country opens the door for the advancement of research led by traditional knowledge, therefore immersing research outputs with Aboriginal ontological philosophies. The contribution of cultural knowledge and practises in research provides an alternative position to the relationship between the environment and Aboriginal communities. Additionally, the exploration of Aboriginal systems of Country and climate is recommended as a valuable addition to future research on climate change and the increasingly frequent, subsequent natural disasters. It is recommended that future research into the impact of climate change as experienced by Aboriginal peoples explore the use of traditional healing practises in response to both the personal and communal effects of environmental change. Continued research in this space will aid the development of post-disaster planning and management whilst informing the development of future adaption policies. Finally, it is recommended that the inclusion of a decolonised, Indigenist lens is essential for future research in this space.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KUp: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Visualization, Writing – original draft. KUs: Funding acquisition, Supervision, Writing – review & editing. VS: Supervision, Writing – review & editing. MM: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Net benefit of smaller human populations to environmental integrity and individual health and wellbeing

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Introduction: The global human population is still growing such that our collective enterprise is driving environmental catastrophe. Despite a decline in average population growth rate, we are still experiencing the highest annual increase of global human population size in the history of our species—averaging an additional 84 million people per year since 1990. No review to date has accumulated the available evidence describing the associations between increasing population and environmental decline, nor solutions for mitigating the problems arising.

Methods: We summarize the available evidence of the relationships between human population size and growth and environmental integrity, human prosperity and wellbeing, and climate change. We used *PubMed*, *Google Scholar*, and *Web of Science* to identify all relevant peer-reviewed and gray-literature sources examining the consequences of human population size and growth on the biosphere. We reviewed papers describing and quantifying the risks associated with population growth, especially relating to climate change.

Results: These risks are global in scale, such as greenhouse-gas emissions, climate disruption, pollution, loss of biodiversity, and spread of disease—all potentially catastrophic for human standards of living, health, and general wellbeing. The trends increasing the risks of global population growth are country development, demographics, maternal education, access to family planning, and child and maternal health.

Conclusion: Support for nations still going through a demographic transition is required to ensure progress occurs within planetary boundaries and promotes equity and human rights. Ensuring the wellbeing for all under this aim itself will lower population growth and further promote environmental sustainability.

KEYWORDS

air pollution, child health, climate change, consumption, environment, overshoot, pediatrics, sustainability

1 Introduction

Growth of the global human population is one important dimension of the rising severity of climate change, but is often not overtly discussed as a driver. For example, the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) did not mention population in its widely disseminated *Summary for Policymakers* (1), although population was discussed in the full report (2). Neither was population mentioned in either the *Paris COP 21 Agreement* (3) or the *Glasgow COP 26 Climate Pact* (4). The reason for this lack of emphasis on the contribution of population growth to environmental decline, including climate change, is unclear, but it possibly stems from sensitivities regarding unclear messaging (5), inequalities between high- and low-income nations, and concerns about challenging the established paradigm that economic growth is necessary for development (6). If the issue of the human contribution to environmental integrity and future wellbeing are to be given proper consideration and discussed rationally, it is essential that the population morass be included in any debates.

The effects of climate change on human health have been the focus of extensive research, but the contribution of population growth to these effects have been largely overlooked. This oversight threatens to diminish recent improvements in global health. Although the global fertility rate is slowly declining, the annual rate of population increase relative to planetary boundaries has not changed in 30 years, with the annual increment exceeding 80 million (7). The contribution of population increase to environmental integrity and resilience remains one of the greatest gaps in understanding. Finding acceptable and ethical solutions to the quandary of population in terms of maintaining resources and human health and wellbeing is therefore urgent. Emphasizing that women and men globally have access to free, non-coercive, culturally and socially acceptable, and high-quality family-planning services is an important component of these solutions in the long term. Indeed, this is one of the United Nations Sustainable Development Goals, but is still a long way from being met (8).

In this review, we summarize the available evidence of the relationships between human population size and growth and environmental integrity, human prosperity and wellbeing, and of course, climate change. After revealing the available evidence, we suggest approaches to mitigate negative repercussions. We review the broad range of ways in which a high and increasing population contributes to increasing consumption, rising emissions, and continuing environmental damage. Given that climate change is the greatest threat to future human health and persistence (2), including the potential to interact with other socio-economic drivers exacerbating conflict (9), we examine the contribution of an increasing population to this threat, including the potential of overshooting current population projections. We examine the evidence for the impact of environmental change, including climate change, on human health, with an emphasis on child health given that 88% of the climate-change health burden is borne by children (10, 11). Finally, we examine the arguments for and against policies to stimulate or reduce population growth globally, nationally, and locally.

We have organized our review into the following sections: (*i*) introduction (*ii*) basics of population projections, how these measures are created, and potential limitations to be considered from existing global population projections, (*iii*) risks from increasing global population size, where we consider the implications of the highest population growth projections ("worst case" scenario), (*iv*) drivers of increasing risk of population overshoot, (*v*) countering arguments against a safe and sustainable global population, specifically addressing the unfounded fears associated with population decline and aging populations, and (*vi*) discussing potential policy pathways to achieve safe and sustainable population sizes globally.

2 Materials and methods

We employed a search strategy in *Pubmed*, *Google Scholar*, and *Web of Science* to identify all relevant peer-reviewed and gray-literature sources examining the consequences of human population size and growth on the biosphere. Our main search terms included: "population," "demography," "fertility," "overpopulation," "population size," "family planning," "projection," and these expanded rapidly to incorporate elements associated with "climate change," "greenhouse-gas emissions," "consumption," "ecological footprint," "biocapacity," "pollution," "biodiversity," "disease," "contraception," "child health," "maternal education," and "population decline." We also followed many additional pathways identified via these search strings to online reports and databases to complete the coverage of available literature. To determine the trends in peer-reviewed publications addressing the joint topics of population and human fertility, we employed the search string "population + fertility" in *PubMed* from 01.01.1970 to 31.12.2022.

3 Results

3.1 Current population projections and risk of overshoot

3.1.1 Human population size and projected trends

There are now over eight billion people living on Earth (12). The world population has increased at an unprecedented rate since the 1700s (Figure 1), and is projected to increase to an average of 10.4 billion people in 2100—a 10-fold increase over 250 years (7).

Several different models project the population trajectory to 2100. The most widely cited are from the World Population Prospects produced by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (7). The United Nations Population Division projections have been updated regularly since 1951, and therefore have broad appeal. Alternatively, forecasts from the International Institute for Applied Systems Analysis-Wittgenstein Centre (IIASA) (13), available since the 1990s, are the most widely used for modeling the contribution of future emissions in climate-change projections (2). Another more recent forecast (from 2020) is by the International Health Metrics and Evaluation (IHME) (14), but with criticism of its methods and results (15, 16).

All population projections have the same starting point: estimates of the number of people alive today tend to be consistent among models, with birth and mortality rates derived from censuses, demographic surveys, or official registers. The differences in projected population size derive from different modeling choices and assumptions when applying estimates of fertility, mortality, and international migration parameters. Some of the main differences in projected outcomes depend on the expectation of how fertility,

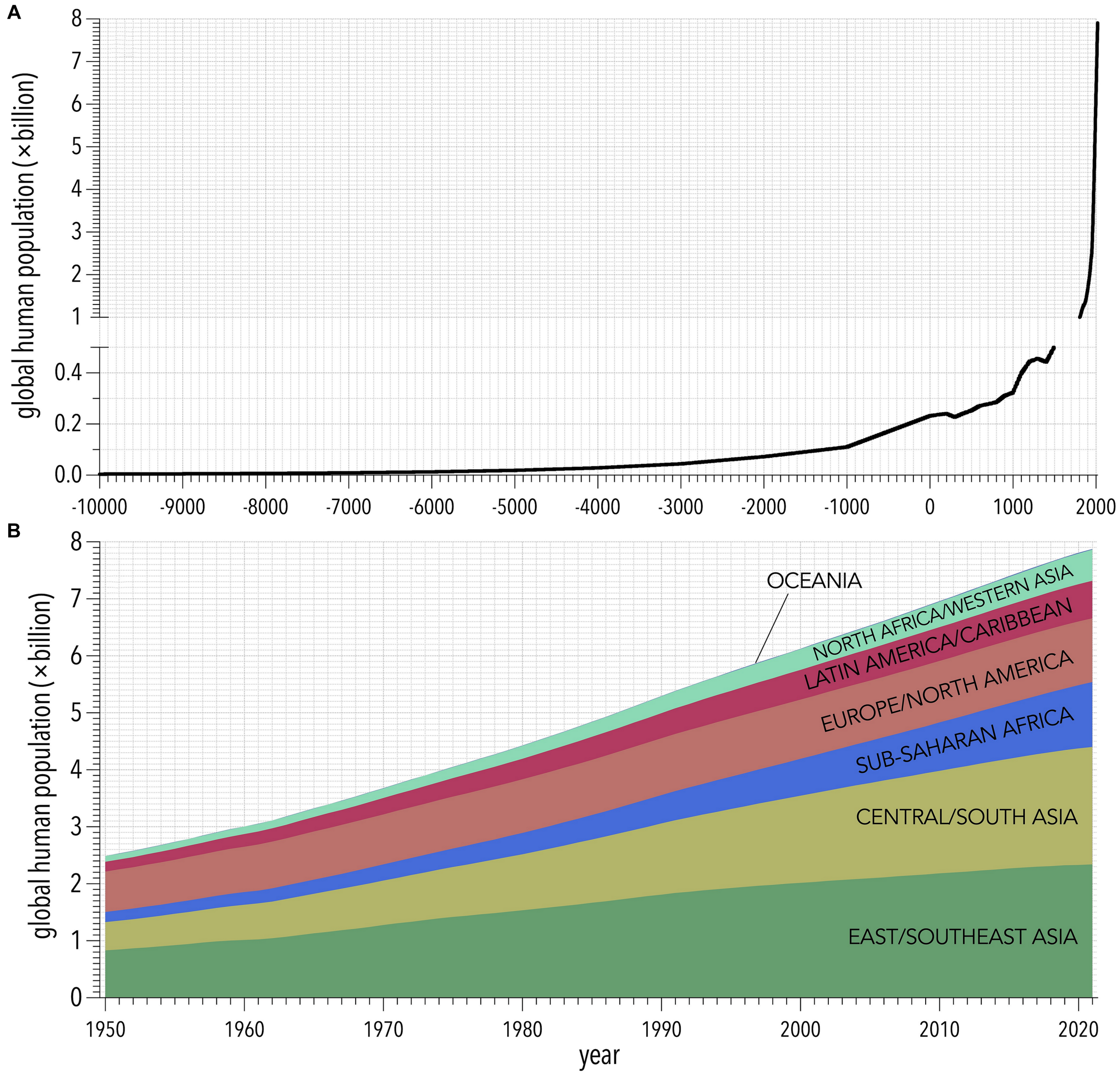

FIGURE 1
(A) Population growth since 10,000 BCE according to the History Database of the Global Environment and the United Nations (12). **(B)** Regional population trajectories from 1950 to 2021 from the United Nations Population Division (7).

mortality, and migration will change with anticipated economic development, as well as how quickly each country might progress through the demographic transition—the theory (17) proposing how nations move from high fertility prior to a decline, followed by a rapid decline in fertility, to plateau eventually at a low fertility.

United Nations Population Division projections use the cohort-component method (18), where existing population dynamics are constructed for each country and projected to 2100. Future survival probabilities, future number of births, and future net migration are projected in five-year intervals using nine projection variants, with five of these variants differing in fertility assumptions (low, medium, high, constant fertility, or instant-replacement fertility), but assuming constant mortality and net migration. The other four variants assume medium fertility but vary mortality and net migration. The 2022 report projects the global population to peak at 10.4 billion people in the 2080s and to remain there until 2100 under its medium variant, and assumes that total fertility rates will continue to decline (7). The lowest-rate variant projects the global population to decline to 8.9 billion by 2100, and the highest-rate variant projects it to rise to 12.4 billion, with this variability arising from an uncertain projection of fertility rates (7). The increasing frequency of pandemics (19) might add uncertainty to forecasts of fertility rate due to the accompanying pattern of a steep initial decline in fertility, followed by gradual increases and a baby boom (20).

The IIASA forecasts take educational attainment into account, in addition to the conventional age and sex structures (13, 21), to project populations in three scenarios based on shared socio-economic pathways derived from both expert opinions and statistical modeling. The *Medium* scenario forecasts a medium pathway for fertility and mortality rates, generally viewed as the most likely from today's perspective. The *Rapid Social Development* scenario assumes rapid increases in life expectancy, a faster decline of fertility rates in currently high-fertility countries, and a fulfillment of the education goals in the United Nations' Sustainability Development Goals. The *Stalled Social Development* scenario assumes a stall in education attainment within developing countries, and continued high fertility and mortality. The 2018 *Medium* projection predicts a global population of 9.8 billion achieved between 2070 and 2080 before slowly declining to 9.5 billion people by 2100. In the *Rapid Social Development* scenario, a peak population of 8.9 billion is projected for 2055–2060 before declining to 7.8 billion by 2100. Assuming the *Stalled Social Development* conditions, the world population is forecasted to be 10 billion people in 2045, with a continued growth to 13.4 billion by 2100.

The main difference between the IHME projections and those from the United Nations Population Division and IIASA is the quantification of fertility. Instead of the conventional total fertility rate, defined by the World Health Organization as the "… total number of children that a hypothetical cohort of women would have at the end of their reproductive period if they were subject during their whole lives to the fertility rates of a given period and if they were not subject to mortality" (22), the IHME instead applies the completed cohort fertility at age 50 (CCF50), defined as the "… average number of children born to an individual female from an observed birth cohort if she lived to the end of her reproductive lifespan" (14). The CCF50 has been proposed as a more stable forecasting method because it corrects for changes in total fertility rate over time rather than assuming the raw values that fluctuate considerably over time, due to lags in the influence of changing age structure, educational attainment, and meeting contraceptive needs. While using CCF50 might improve the stability of projections, larger influences on variation among models are the specific assumptions regarding the trajectories of future fertility, education, age structure, and other development indicators. The IMHE projections consider four alternative scenarios with differences in education and family-planning policies. De-prioritizing education and family planning through policy changes increased projected population sizes. The lowest-rate forecast assumed increased female empowerment through better education attainment and increased access to contraception (14), resulting in a lower growth rate than the *Medium* variant of the United Nations Population Division projections—this projects the global population to peak at 9.73 billion just after mid-century and then a decline to 8.79 billion people by 2100 (14).

Accurate population projections are an important tool in shaping the future of human societies primarily through their effects on national policies—for example, planning for health care, housing, childcare, and schools, or anticipating economic development (15, 16, 23). We discuss the interaction between projections of population size and these policy dimensions below. Of the three projections highlighted, the IHME's has been most criticized for proposing less-realistic and least-verifiable assumptions (24). The corollary is that unsubstantiated lower projections to 2100 could potentially mislead governments to implement coercive policies such as restricting access to contraception to increase fertility to a replacement rate. The argument for this is usually driven by a misplaced fear of stagnation in the country's economy, the arguments against which we discuss in subsequent sections.

There is a lack of rigorous evaluation of existing population projections in terms of relative assumptions and realism of proposed scenarios. A necessary analysis of existing projections under various scenarios would clarify the relative likelihood of different population trajectories over the course of the coming century. While the three institutions responsible for the described projections include working groups of experts, an external and independent evaluation would guide future improvements and provide more realism. Regardless, the most likely outcomes based on mid-range assumptions and scenarios indicate that a global population between 9 and > 10 billion by the end of this century is the most parsimonious.

3.2 Risks from increasing population sizes

3.2.1 Consequences of a growing human population

Large human populations pose a risk of global catastrophe due to their influence on increasing environmental risks such as changes in atmosphere and climate, land degradation, and threats to biodiversity. Fundamentally, continued population growth leads to an increase in human economic activity, which puts pressure on the planet's ability to renew resources (25). Population growth increases pressure and competition for finite resources such as food, water, and land; to compensate, production must rise, resulting in even greater environmental damage (26–28). With fewer people in the past, whenever environmental damage occurred, groups of people usually colonized other places or otherwise survived at lower densities (25). With today's already large global population, the option to colonize new regions is unfeasible and instead drives additional environmental damage (26, 28). The causes for these global environmental risks are not necessarily clear, so we consider the following main environmental problems arising from population growth: (*i*) greenhouse-gas emissions and temperature increases, (*ii*) pollution, (*iii*) loss of biodiversity, and (*iv*) spread of infectious diseases and general worsening health outcomes.

There is a strong theoretical basis for expecting a positive relationship between human population size and the risk of environmental erosion that are encapsulated by several mathematical concepts. Existing models built to quantify environmental impact arising from population pressures, such as the IPAT (**I**mpact [emissions] = **P**opulation × **A**ffluence × **T**echnology) (29), ImPACT (**I**mpact = **P**opulation × **A**ffluence × **C**onsumption [intensity of use] × **E**fficiency [emissions per unit energy used]) (30), and STIRPAT (a stochastic variant of IPAT) (31), were developed mainly to determine the role of factors such as population growth and technological change in affecting environmental degradation. These equations and their variants can ideally predict the environmental outcomes of particular policy adjustments (32, 33). For example, the ImPACT equation was constructed to assess total emissions as a function of population size, *per capita* gross domestic product, energy consumption per unit gross domestic product, and CO_2 emissions per unit energy consumption (30). The following subsections reveal the extent to which the population component of impact equations cannot be neglected.

3.2.2 Greenhouse-gas emissions and climate disruption

It is axiomatic that an increasing population produces more emissions, but this simple relationship belies a complex interplay between consumption rate itself, and the total number of consumers. We explore this concept contextually before considering the consumption and production pathways resulting in different emissions profiles.

Increased concentrations of greenhouse gases generated from energy consumption, predominantly from burning fossil fuels, have contributed greatly to global environmental degradation. The Intergovernmental Panel on Climate Change (IPCC) Assessment Reports show that increasing emissions translate to additional global warming, reduced air quality, changes in the global water cycle, and increased prevalence of extreme climate events such as high rainfall and flooding, fires, droughts, and cyclones (34), with all the associated secondary adverse health impacts. Population growth has resulted in more human enterprise, and therefore, more intensive energy consumption (35). As new technology is developed, the energy consumption *per capita* also grows (27, 28). Indeed, the annual per-capita rate of global primary energy consumption increased 1.62 times since 1965 to today (46.7–75.6 GJ person^{-1}), or an average increase of 0.41 GJ person^{-1} year^{-1} (Figure 2) (36). During that same interval, the global human population increased from 3.3 to 8.0 billion (Figure 1) and total annual greenhouse-gas emissions increased from 11.2 Gt to 33.0 Gt CO_2-e (36).

A combination of more consumers and higher consumption rates drive the growth in greenhouse-gas emissions, rather than population growth alone (37). Nations with low per-capita emissions tend to have the highest population growth rates (38), meaning that if they follow the development trajectories of high-income nations today, emissions will also continue to grow. The latest IPCC report predicts a 1.7°C increase in global temperatures relative to pre-industrial temperatures (i.e., average of the 51-year period from 1850 to 1900) by 2060 under a scenario of low population growth versus 2.8°C warming with a medium-high scenario of population growth (34, 39).

Consistently throughout history, there is a concomitant rise in per-capita energy consumption with population growth (35). As people gradually deplete resources in their environment, innovators find new ways to extract energy from previously unused resources or import resources from less-depleted locations. Increased energy use from these new resources facilitates improvements in diet and living standards, which stimulates even more population growth (26, 35, 40). This phenomenon is summarized succinctly by the concept of the *ecological footprint*, which describes how much biologically productive area is required to provide for all the competing demands of the people it services, such as space for agricultural and fiber production, timber, sequestration of carbon dioxide emitted from burning fossil fuels, and built infrastructure (41) (Figure 3). This area can be calculated for the entire globe, or individual nations, leading to the estimate of *biocapacity*, which is the amount of biologically productive land and sea available to provide the resources a particular population consumes and to absorb its wastes (given current technology and management). Globally, we are operating on a biocapacity deficit that is consuming Earth's ecosystems 1.7 times more rapidly than they can be renewed.

Greater consumption of manufactured goods increases waste and subsequently leads to increased consumption of resources to manage that waste, creating a self-perpetuating, vicious cycle. Food-waste management alone accounts for 8–10% of global human-produced greenhouse-gas emissions year^{-1} (approximately half of that emitted by the entire global food system) (43, 44). Solid waste management adds another 5% (45). Carbon-removal technologies such as carbon capture, carbon sequestering, and other proposed "net zero" solutions will not themselves counter increasing consumption. While appealing in principle, these technologies are logistically difficult to implement at scale such that net emissions decline. Relying on such technologies is dangerous because it diminishes the sense of urgency to reduce consumption and emissions now (46).

Population growth is the main driver of water scarcity because larger populations have higher water demand (47, 48) in the absence of major technological and policy shifts to disrupt the dependency of demand and supply (49, 50). Freshwater resources are finite, but the demand for water in food production continues to grow. Irrigated agriculture, rain-fed agriculture, and livestock production on pastureland all require freshwater. Subsequently, population growth exacerbates environmental risks by requiring greater food production (40, 51).

The agriculture sector contributes over a quarter of the world's greenhouse-gas emissions, from agriculture, forestry, and land-use change (52–55). Agriculture accounts for approximately 20% of global, human-produced greenhouse-gas emissions annually (55), while livestock contributes 14.5% (56). Food production emits 45% of total methane (CH_4) globally, where 80% is from livestock production, and rice production is the next-largest emitter. Agriculture is also responsible for 80% of nitrous oxide (N_2O) emissions globally, mainly from fertilizer application (57). Methane and nitrous oxide are more powerful than carbon dioxide (CO_2) in forcing temperature increases over a span of 20 years by a multiple of 84 times and 264 times (55), respectively. Together, CO_2, CH_4 and N_2O concentrations have increased over the industrial era from human activity, resulting in unequivocal warming of the global climate system (34).

Reducing emissions in agriculture is challenging because the sector (*i*) is slower to change than other major industries, (*ii*) is fragmented, and (*iii*) has a complicated set of objectives. Unlike the electricity sector, where it is possible to displace coal and gas with low-emissions technologies (58, 59), these options are not available for agriculture. Another contributing deterrent of rapid, broad-scale change is the large proportion of small stakeholders. Most farmers (2 billion globally) are employed on small farms (smallholders) in developing countries (60), meaning 65% of working adults in low-income countries make a living through agriculture. The risk of failure or lower yields in the short term is therefore untenable despite potential long-term gains for reducing emissions at the farm scale (60). Most emissions-reduction measures, such as more sustainable farming practices, would either reduce costs or be cost-neutral; however, they are not implemented due to capital constraints, limited access to technology, and adherence to local traditional practices, all exacerbated by the scale of smallholdings (53). Additionally, agriculture impacts biodiversity preservation, nutritional needs, food security, and livelihoods. Forests in developing countries are, on average, cleared twice as fast as they can grow back (61), leading to the concern that soil erosion and desertification from deforestation combined with intensive agriculture threatens up to a third of the Earth's total land surface. Financial support and capacity building for smallholders are essential to bring the agricultural sector to a more sustainable path and to fulfill its goals of reducing emissions.

As the human population continues to increase, awareness of what we eat and how much food we waste (consumption-side management) is essential. Managing food waste is the most impactful

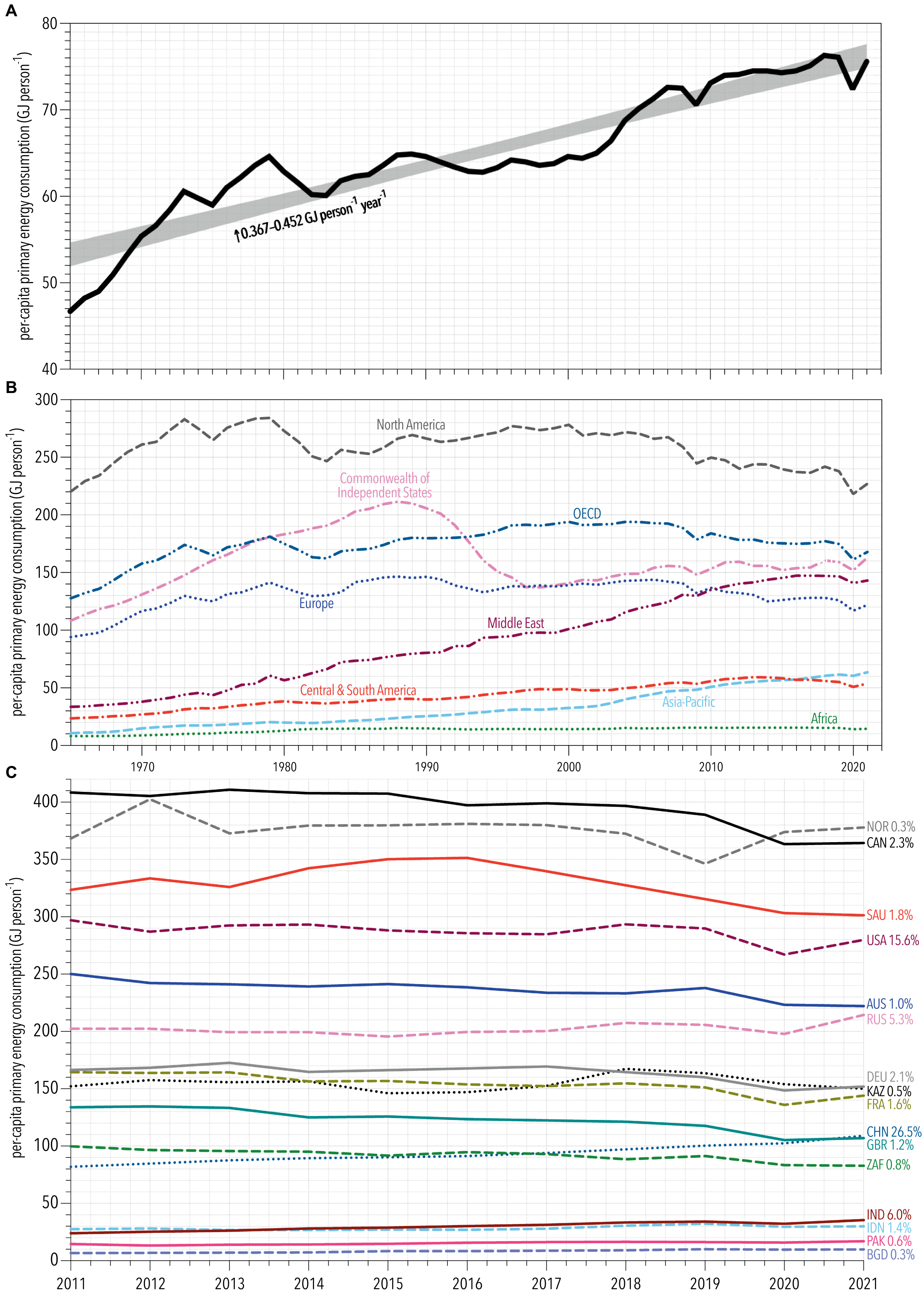

FIGURE 2

(A) Per-capita annual primary energy consumption from 1965 to 2022 (36), equating to an average increase of 0.41 GJ person^{-1}year^{-1} (95% confidence interval: 0.367–0.452 GJ person^{-1}year^{-1}). **(B)** Regional per-capita annual primary energy consumption over the same interval. **(C)** Trajectories of per-capita primary energy consumption from example countries covering the broad range. Percentages next to the country abbreviations indicate the share of total global consumption in 2021 (36). Countries shown: NOR, Norway; CAN, Canada; SAU, Saudi Arabia; USA, United States; AUS, Australia; RUS, Russia; DEU, Germany; KAZ, Kazakhstan; FRA, France; CHN, China; GBR, United Kingdom; ZAF, South Africa; IND, India; IDN, Indonesia; PAK, Pakistan; BGD, Bangladesh.

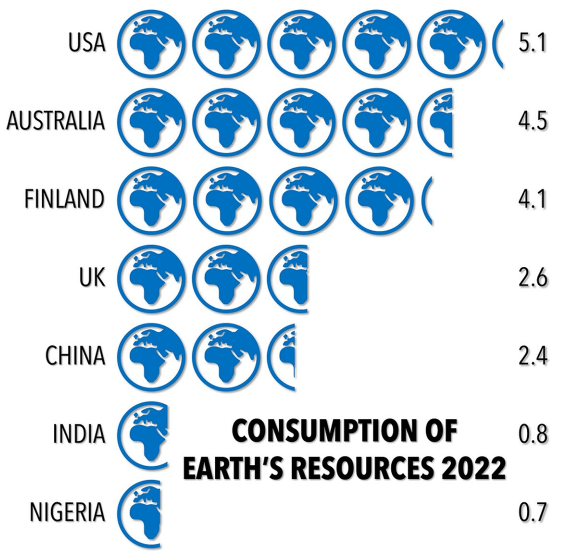

FIGURE 3
Our global ecological footprint using seven example nations: USA, Australia, Finland, United Kingdom, China, India, and Nigeria (41, 42). The numbers on the right indicate how many Earths would be required if everyone on Earth consumed renewable resources at the same rate as the nation indicated.

because approximately one-third of all food produced is never consumed (62). Wastage occurs across the supply chain during production, transportation, and storage due to lack of access to technology and cold-storage infrastructure. It also occurs at the retail and consumption phases, especially in higher-income regions due to aesthetic preferences, purchasing more food than needed, and poor portion control. If food waste were to fall to <30% by 2030 and <20% by 2050, there would be an overall reduction in greenhouse-gas emissions from food waste by about 40% globally (62).

Although a much smaller effect, consumption should be considered when reducing the sector's emissions. As people become wealthier, demand for meat consumption tends to grow (63). High-income countries consume between 60 and 91 g day^{-1} of meat, while countries in Asia and Africa consume only 4–7 and 7–34 g day^{-1}, respectively (64). Meat consumption and production are environmentally costly; food systems are responsible for 21–37% of global greenhouse gas emissions, and of that, 52% is caused by cattle products alone (65).

The common denominator for all these issues is population growth. Despite implementing the solutions proposed above specific to each outlined problem, if the global population keeps growing beyond a safe space for the planet, we will still experience disastrous consequences. Indeed, the most effective individual action in addressing the emission and consumption issue is to have one fewer child (66).

3.2.3 Pollution

Despite ongoing efforts by United Nations agencies, committed groups and individuals, and some national governments (mostly in high-income countries), little real progress against both air and water pollution is being made overall, particularly in the low-income and middle-income countries where pollution impacts are most severe (67). Deaths from ambient air pollution have increased over the last two decades, accounting for 2.9 million premature deaths in 2000, increasing to 4.2 million in 2015, and 4.5 million in 2019 (67). Premature deaths due to all forms of pollution have remained unchanged at 9 million from 2015 to 2019 (67). *The Lancet Commission on Pollution and Health* cited pollution as "… the world's largest environmental risk factor for disease and premature death" (67).

There is also a growing concern for water quality—population pressure, unsustainable consumption, and unsustainable production stress can degrade freshwater resources (47). In the past, smaller settlements relied on the self-cleansing and dilution potential of rivers when disposing effluent. These natural functions reach their limits with greater population density and increased industrial production, calling for increased regulation of effluent disposal (47).

More waste resulting from an increase in consumption of manufactured goods also increases pollution, with low- and middle-income countries disproportionately burdened by environmental destruction through pollution due to inadequate infrastructure for waste management—up to 93% of all waste in low-income countries is dumped without further processing (45). This poor management of waste through open dumping or uncontrolled burning pollutes soil, water (68), and the air, subsequently reducing crop growth (69), increasing water scarcity, and damaging human health (45).

3.2.4 Loss of biodiversity

Resource extraction beyond the regenerative potential of Earth is responsible for biodiversity loss, but work remains to identify the relative impact of different mechanisms, and temporal and spatial scales, of the degradation ensuing. The challenge is teasing apart the effects of consumption *per se*, and overall population size—as in all forms of anthropogenic damage to the biosphere, the product of consumption and number of consumers is the combined driver of biodiversity loss. Currently, an annihilation of Earth's biodiversity is underway because of human endeavor, such that we are now firmly within the sixth mass extinction event (70, 71).

An increase in human population size is generally correlated with worse outcomes for biodiversity health in protected areas (72). Human population density and growth rates are disproportionately higher in Biodiversity Hotspots (areas with exceptionally high species endemism and concomitant threats from human agency) (73, 74), which subsequently leads to higher deforestation rates and species loss (75). Historically, an increase in human population size is associated with greater threats to biodiversity (76, 77), and strongly associated with an increased number of threatened species (78–80). Factors contributing to species threat include habitat destruction and degradation (71), direct exploitation such as hunting (81), invasive species (82–84), pollution (85, 86), diseases (87, 88), climate change (89, 90), and the synergies emerging from these different drivers (91).

Another component of biodiversity loss is land-use conversion for human activities such as agriculture, mining, logging, establishing transport networks, and urbanization. Eight times as much temperate grassland is converted for human purposes than is protected (92). Agriculture is the largest driver of biodiversity loss worldwide (52, 93), with a third of the world's land surface already converted for agriculture (94, 95), and over half of the world's wetlands drained and repurposed for agriculture in the last century (96, 97). The global livestock sector is rapidly growing and intensifying, with livestock usually displacing local fauna (56, 98). The expansion of plantations and pastoralism since the 1980s has resulted in tropical deforestation (99, 100). Large herbivore and carnivore species on land also have declining populations due to agriculture (101–103); for large carnivores such as lions, most are pre-emptively hunted because they are threats to humans and livestock (104, 105). In the ocean, examples of destruction of the environment include overfishing (106), trawlers destroying ocean habitats (107–109), and the extinction of large fish species (110). The indirect driver of all this destruction is population growth as we ramp up agricultural production to keep pace; the World Resources Institute has estimated that we need to close a 56% food gap between calories produced (as of 2010) and those needed in 2050 if the global population was to rise to 10 billion people (111).

3.2.5 Spread of disease

Increasing human population means more people living in urban areas (from 43% in 1990 to 54% in 2015) (112). If population growth continues at a similar rate, around 68% of all people will reside in urban communities by 2050, with most urbanization occurring in African countries (112). Rapid urbanization underlies an increasing prevalence of non-communicable diseases in low- and middle-income countries, which account for 85% of premature deaths (between the ages of 30 and 69 years) from noncommunicable diseases worldwide (113). The most prevalent of these include cardiovascular disease, cancers, chronic respiratory disease, and diabetes, all of which have common behavioral risk factors such as poor diet, limited exercise, smoking, and drinking alcohol (114, 115). Additionally, people with a non-communicable disease are at increased risk of some infectious diseases such as tuberculosis or COVID-19, or experience worse health outcomes, such as antiretroviral therapy-treated people living with HIV infection (114). This burden of disease is a threat to economic development by affecting the productivity of working-age people (114).

Urbanization affects the young through a reduction in fertility rates and reduced risk of child undernutrition (115, 116), but an increased risk of becoming overweight (115). Modeled outcomes from 73 countries showed that while children living in urban slums have better health outcomes than rural children, they are not as good as children living in better-off urban environments (116). Urban children, both poor and rich, have reduced mortality and stunting compared to rural children, but increased recent episodes of illness (116).

The associations between urbanization and infectious disease are many and complicated, leading to either increased or reduced risk depending on context (112, 115). Rapid urbanization is strongly linked to informal settlements (slums) that lack basic infrastructure (water and sewerage access) and are overcrowded (higher population density), which can heighten the spread of infectious pathogens (112). Yet, urban communities can provide more accessible health-care facilities and socio-economic opportunities that can lead to improved health outcomes (115). Urban risk factors encompass two main groups: (*i*) geographic, including population density, the built environment, municipal services, and the natural environment; and (*ii*) behavioral, including hygiene and sanitation, education and employment, sexual behaviors, and socioeconomic conditions (112).

With rising urbanization comes increased population density and higher prevalence or transmission of infectious diseases including tuberculosis (117, 118), yellow fever (119), Ebola (120), and HIV (121, 122), particularly in slums. Even within households, risk increases directly with household size (112). Human-to-human disease transmission increases largely due to close contact, while high population density can expose more people to vectors of disease. For example, despite highly effective mosquito-control programs in the high-income nation of Singapore, human population growth and rapid urbanization have enabled far fewer mosquitos to infect the overcrowded population and increase the prevalence of dengue fever (123). Furthermore, as global warming extends the length of the transmission season of mosquito-borne diseases, urban communities will be disproportionately burdened (124). Climate change poses a novel situation in which vector-borne diseases are able to be introduced to and survive in immunologically naïve populations (125). This is reflected in dengue becoming the most rapidly spreading mosquito-borne disease worldwide, with a 30-fold increase over that last 50 years as climates on the fringes of tropical and subtropical regions change to facilitate its spread (126). Within Australia, this is mirrored in migration and increasing burden of Murray Valley viral encephalitis and Ross River virus (127).

The built environment has differing impacts on the risk of infectious disease in humans. Irregularly or sparsely built-up urban areas have higher malaria risk, while densely built areas closer to the city center have reduced malaria risk (128). However, the magnitude of this disparity depends on localized environmental conditions such as proximity to dense vegetation, bodies of water (hydrographic network (128), artificial lakes and dams), or swampy areas, which all increase malaria risk (129). The risk of dengue fever is magnified in urban slums through inadequate drinking water, rubbish collection, and drainage of surface water, leading to increased mosquito breeding and consequent pathogen transmission (130). Conversely, improved health-care access in urban areas compared to rural can improve health outcomes. Malaria is an example of an infectious disease whose expansion has been aided by climate change, global temperature rise in particular. A 1°C increase in mean and minimum temperatures in Nepal led to a 27% incidence increase of malaria countrywide and 25% increase in geographical regions impacted by the disease (131). Likewise, warming is pushing upwards the maximum elevation of malaria in the highlands of countries like Ethiopia and Colombia (132).

Multiple aspects of the quality of house-building have been implicated in the prevalence of infectious disease, with irregularly or poorly built homes associated with increases in respiratory diseases, malaria, and helminth infections (112). Furthermore, rapid urbanization often goes hand in hand with a lack of municipal services such as hygiene (rubbish collection and waste management/disposal), sanitation, and healthcare services, which greatly increase the risk of some infectious diseases. A lack of household latrine and drainage systems has been associated with increased incidence of cholera (133, 134), bacterial and protozoal enteric infections (135), and diarrhea in children (136).

Higher population densities in urban areas can directly increase the risk of poor health outcomes. Increasing urbanization across Africa in particular has been associated with more deaths from air pollution as countries develop economically with increasing industrialization (67). While factors of the natural environment such as wetness and temperature can increase the risk of infectious diseases in urban and rural areas alike, population density in urban areas can increase transmission (112, 133, 137).

Zoonotic transmission of diseases accounts for an estimated 61% of human pathogens and 75% of pathogens that are deemed emerging (138). The occurrence of zoonotic transmission in regions experiencing rapid urbanization is becoming commonplace with expanding consequences. The severe acute respiratory syndrome (SARS) outbreak in 2003 (139), H1N1 influenza pandemic of 2009, Middle Eastern respiratory syndrome (MERS) outbreak in 2012, and of course, the COVID-19 pandemic, are well-documented diseases that have all been facilitated by rapid urbanization (140). Migration and travel both between rural and urban areas, and more globally, can swiftly disseminate disease. Proximity of an urban community to some animal populations, exacerbated by deforestation, forest degradation, and biodiversity loss more generally (141), can have profound impacts on the epidemiology of infectious diseases. Waste accumulation from human habitation encourages rodents and stray animals, plus water storage can enable mosquito proliferation, both of which can increase the chance of spreading a zoonotic disease in urban areas (142). Emergence or re-emergence of infectious diseases through increased interaction at the wildlife-livestock-human interface, at areas of steep transition between ecosystems (known as "ecotones"), can increase the likelihood of disease transmission between species. This is confounded by climate change and biodiversity collapse, both associated with large population sizes, which increase the risk of pathogen exchange at the human-animal interface (125). Evidence of disease emergence at ecotones has been documented for yellow fever, Nipah virus encephalitis, influenza, rabies, hantavirus pulmonary syndrome, Lyme disease, cholera, *Escherichia coli* infection, and African trypanosomiasis (143). Land-use change, particularly deforestation, has increased proximity of humans with wildlife directly, or through livestock that interact with wildlife (142). Livestock production that overuses and misuses antibiotics can increase antibiotic-resistant bacterial strains, which are transferable to humans through direct contact with infected animals, consumption of contaminated food, or via the environment (water, soil, air) contaminated by animal waste (144).

Rapid urbanization often occurs without adequate planning, leading to more violence, conflict, and crime. This burden disproportionately affects women, migrants, and refugees, with impacts on security, livelihoods, health and access to services (145) (Figure 4).

Increasing prevalence of urbanization can be expected to continue and can be beneficial to delivery of health services if accompanied by informed planning and policy. The faster urbanization occurs (with a rapidly increasing world population), the less planning will happen (slums emerge much faster than planned urban developments, especially in sub-Saharan Africa) and therefore, more of the negative effects of urbanization are likely. This is complicated by climate change that increases the prevalence of many infectious and non-infectious diseases (125). In short, the 2021 Australian State of the Environment report stated it best: "Environmental degradation is now considered a threat to humanity, which could bring about societal collapses" (146).

3.3 Risk of overshoot

The steady rise of publications investigating human fertility and population that we identified using a search of the online engine *PubMed* (date range 01.01.1970 to 31.12.2022) dwindled sharply following the landmark 1994 International Conference on Population and Development held in Cairo (32) (Figure 5). That conference sparked a pivotal change in international discussions regarding population from the starting perspective of global population "control" through increased access and quality of family planning, to an individual-based model focused on improving the rights of women and girls through access to education and reproductive health services (33, 147). However, the meeting was dominated by voices from the Vatican and their views around contraception and abortion, which denuded discussion of topics such as the environmental impacts of population growth. This remains an ongoing issue because international policy discussions today still stifle the conversation on population. The United Nations Sustainable Development Goals do not mention slowing population growth, with only one Goal (3.7 *Good Health and Wellbeing*) mentioning universal access to sexual and reproductive health-care services (148). This lack of prioritization is further demonstrated because the role of population in international policies today is analyzed by a subsidiary group of the United Nations (United Nations Population Fund), who are supported only through voluntary contributions from governments and not through a regular budget (149).

Projections of population increase are inherently unreliable because the ultimate expression of future population depends heavily on even small changes in total fertility rate per country (see section 3.1.1). Intelligent discussion on overpopulation has also been inhibited due to concerns of "population control" related to past abuses arising from autocratic measures to limit fertility (150). Providing women and men the opportunity to determine the number and spacing of their children, free of coercion is not, by definition, "population control," and was internationally recognized as a basic human right in 1968 (151). In particular, empowering women, especially disadvantaged women, to be able to make decisions about when and how many children they intend to have, improves their own lives as well as those of their children, and is a proven path to successful development (152). In 2006, only around half of the world's population lived in countries with fertility rates at or below replacement, notably only in high-income countries (153).

Below we discuss some of the factors that lead to women choosing to have more children, thereby increasing fertility rates. There are many influences on a woman's total fertility rate; we distill these into the following main categories: (*i*) demographic drivers, (*ii*) lack of access to contraceptives, (*iii*) child and maternal health, (*iv*) maternal education, and (*v*) social and cultural factors. We also discuss the principle that determining the optimal, case-by-case family size should not be left to women alone; men should also be provided with the education and free access to effective male contraception, allowing them to contribute actively in family-planning decisions.

3.3.1 Demography

The age at which women first give birth has a large impact on fertility rates, with an average younger age at first birth reducing the intergenerational gap, and increasing fertility rates over time (153). For example, if all women in a society started having children at the age of 20 years as opposed to 25, the population would be at least 20% larger in 100 years (assuming other factors remain unchanged) (154, 155). However, exceptions to this pattern have been observed within East Africa and Afghanistan, where subnationally, the highest teenage fertility rates do not always correspond with the highest fertility rates

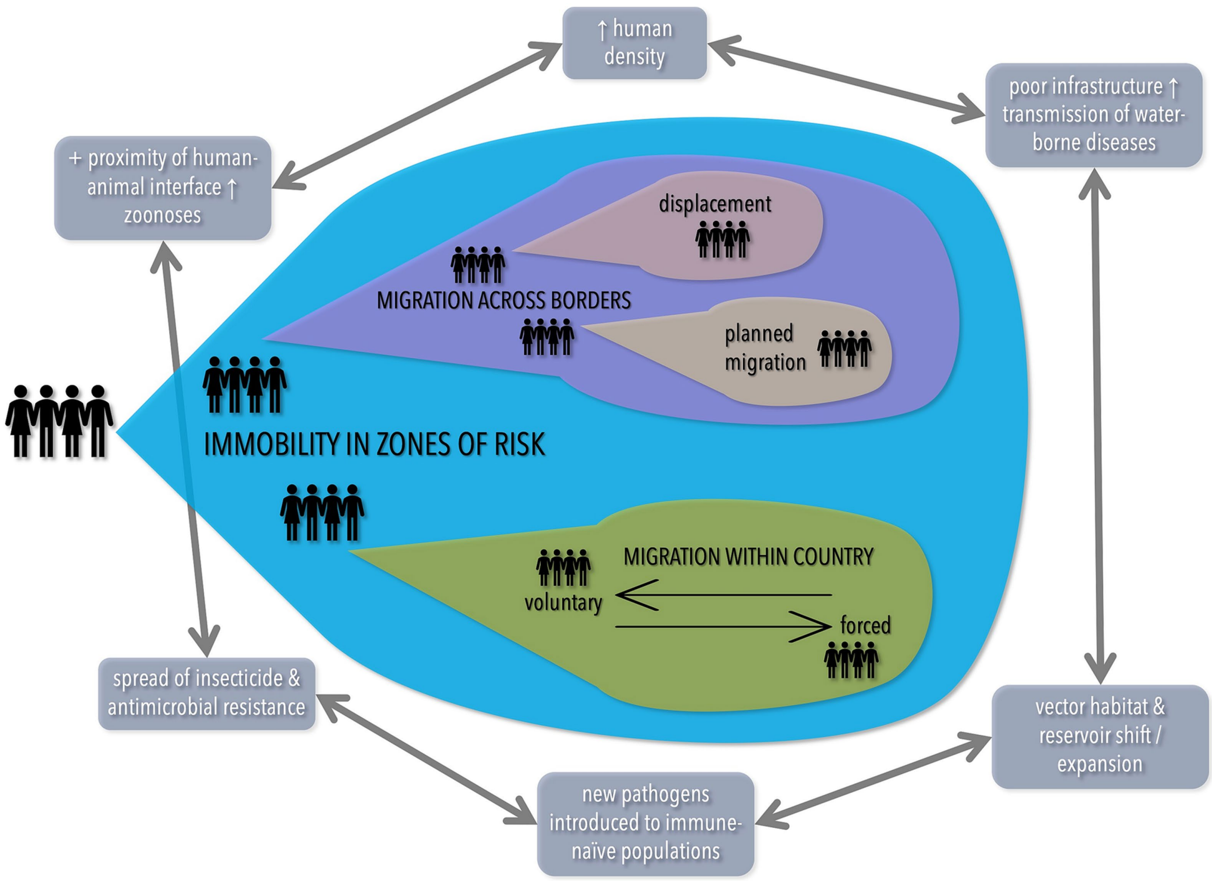

FIGURE 4
Population density, climate change, and poor infrastructure/planning all interact to lead to increased risk of disease. Adapted with permission from Wiley (Ref. 125), © 2021 Paediatrics and Child Health Division (The Royal Australasian College of Physicians), https://doi.org/10.1111/jpc.15681.

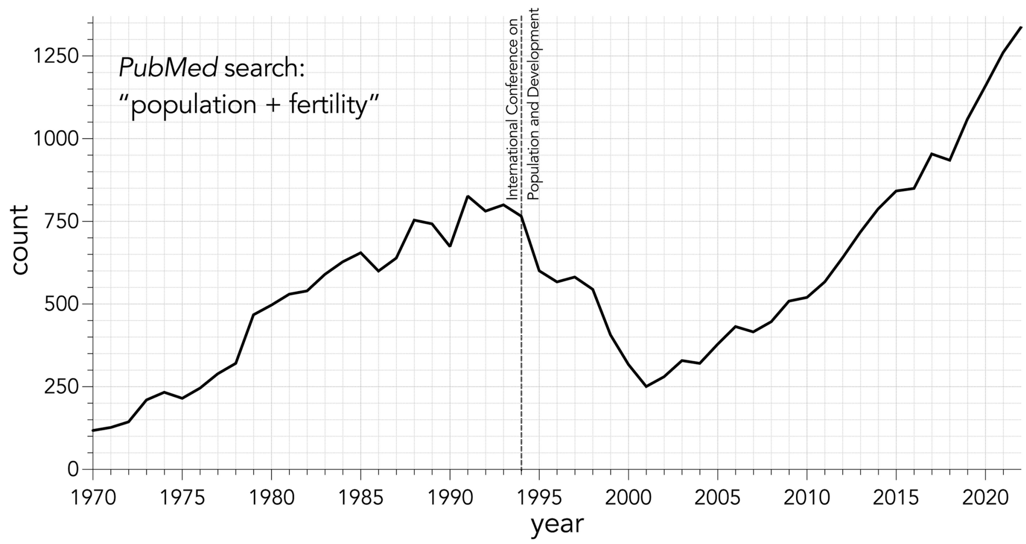

FIGURE 5
Annual total number of articles identified from *PubMed* using the search string "population + fertility" from 1970 to 2022.

(152). This indicates the influence of additional behaviors and social norms, bearing in mind that East Africa and Afghanistan have some of the highest total fertility rates globally (152). Conversely, older average maternal age at first birth reduces reproductive lifespan, producing a lower average number of total children and lowering fertility rates overall (153, 156). Population (or "demographic") *momentum*, a natural consequence of the demographic transition (154), where high fertility rates of the previous generation increase population growth in the current generation even when fertility rates are declining (157), is another contributor to higher population growth rates (158).

3.3.2 Lack of access to contraceptives and unintended pregnancies

An estimated 270 million women had an unmet need for family planning in 2019 (159), 85 million of which used traditional rather than modern methods of contraception (160). This number rose from 232 million in 1990 and is expected to rise to 272 million by 2030, mainly due to family-planning services in developing countries not keeping pace with the rapid population increase (159). Globally, approximately half of all pregnancies in 2015–2019 were unintended, which equates to 121 million unintended pregnancies annually (161). There is a strong inverse relationship between unintended pregnancy and World Bank income group, with sub-Saharan Africa experiencing the highest rate of unintended pregnancy, and Europe and North America, the lowest (161). Not every unintended pregnancy is unwanted; however, an estimated 61% of unintended pregnancies end in abortion, totaling 73.3 million abortions annually (161). In countries where abortion is restricted, the proportion of unintended pregnancies that end in abortion has increased since the early 1990s, and their rates of unintended pregnancy were higher than in countries where abortion was legal (161).

The post-Cairo framing on women's rights primarily had an unintentional negative impact of taking the focus off access to family planning, and thus led to some governments deprioritizing family planning. This has occurred recently, with the UK government cutting 85% of its annual funding to the United Nations Population Fund (162). Domestic politics can also play a large role on global family planning services; for example, the major global funder, the United States Agency for International Development (USAID) has precluded the provision of abortion since 1984 under the "global gag rule" by anyone receiving those funds (163), depending on the sitting US president.

Access to contraceptives and non-coercive, quality family-planning services are mechanisms to help populations from attaining a size that generally reduces the standard of living, health, and wellbeing. Indeed, in sub-Saharan Africa where large families are common, the availability and quality of family-planning services had the largest effect on fertility of any explanatory variable (0.83 fewer births per woman) (164). However, subsequent research demonstrates that most variation in fertility among low- and middle-income nations can be explained by variation in child mortality, followed by household size (a proxy for population density), and then access to any form of contraception (165). That family-planning services educate parents about the benefits of investing in fewer children has been observed previously (164).

In addition to lowering fertility, family planning also improves the health of mothers and children. Contraceptive use, by reducing the number of births, therefore reduces the number of times a woman is exposed to birth-related mortality risks, and also reduces the incidence of problems arising from high-risk, high-parity births (166). Maternal mortality remains the leading cause of death and disability in reproductive-age women in low- and middle-income countries (167), with one study estimating over 1 million maternal deaths were averted between 1990 and 2005 in low- and middle-income countries through access to contraception (166). In 2008, an estimated 342,203 women worldwide died of maternal causes, with contraceptive use averting 272,040 deaths (preventing 44% of probable mortality), and if the unmet need for contraception was satisfied, another 104,000 maternal deaths could have been avoided (29%) (168). In Indonesia, contraceptive use averted an estimated 523,885–663,146 maternal deaths between 1970 and 2017 (169).

Contraceptives and other family-planning services allow women to modify the risks that come with pregnancies that are "… too early, too late, too many, or too frequent" (170). Shorter birth intervals were associated with higher infant and child mortality in a large longitudinal study in Bangladesh (171), thereby supporting the maternal depletion hypothesis where high fertility does not allow a woman to recuperate sufficiently from the nutrient/energy depletion caused by the first pregnancy or breastfeeding event to support a subsequent pregnancy (171). Longer birth intervals can increase the probability of nutrition repletion, which can positively affect fetal growth and newborn survival, although the results are equivocal among studies (172). Birth spacing of >24 months reduced the probability of child stunting in Indigenous communities of India, with increased access to family planning suggested as a major intervention to enable improved child health (173). Other mechanisms that might influence mortality risk of a short birth interval include sibling competition for parental time and resources, maternal wellbeing, and increased risk of disease transmission among similarly aged siblings (171). Furthermore, a short birth interval reduces infant survival (174, 175), thereby simultaneously increasing the woman's probability of having another child, and reducing the time to the next birth (consistent with "replacement" behavior (176), whereby infant death truncates breastfeeding and reduces protection against fertility) (177).

When a young mother dies, there are cascading effects beyond the motherless infant. In 1990, 585,000 women died from pregnancy-related causes, leaving behind at least 1 million motherless children (170) who have twice the risk of dying compared to children whose father had died only, and daughters almost twice as likely to die compared to sons (170). Similarly, an Ethiopian study concluded that a maternal death imposed an increased chance of the infant dying 46 times higher than if the mother had survived (167). The HIV/AIDS epidemic has resulted in approximately 17 million children who lost one or both parents, with 90% of those children living in sub-Saharan Africa (178), and devastating consequences for individuals and communities (179). Given the dire consequences, it is surprising that access to safe, effective, affordable, and acceptable family-planning services has not improved since the 1994 Cairo meeting. In response, the 2012 London Summit on Family Planning developed goals for improved access, which have not yet been met (180).

Despite the overall stalling of family planning globally, there are successful examples in low- and middle-income nations due to political will and government leadership. Between 2005 and 2015, the Rwandan Government expanded and promoted family planning, increasing the use of contraceptives from 17 to 53% (181). Similarly, the Ugandan Government also recognized the immediate need for access to family planning and has pledged to increase funding (182), given that rapid population growth coupled with a high young-age dependency ratio (more young people than working-age people) is economically unsustainable and will prevent Uganda attaining middle-income status (182). Policy implemented over 5 years has already provided 1.5 million women with family-planning services and averted 8,000 maternal and 100,000 child deaths, and saved over US$300 million in pregnancy-related health-care costs.

3.3.3 Child health

Infant and child mortality has declined rapidly, with global infant mortality moving from 98.5 deaths/1000 live births in 1970 to 27.9 deaths/1000 live births in 2021 (i.e., a 3.5-fold reduction) (7). However, this impressive reduction belies high regional variability, with low- and middle-income countries disproportionately concentrating up to 99% of the world's child mortality (sub-Saharan Africa 49 deaths/1000 live births, and South Asia 30 deaths/1000 live births) as of 2021 (7). Additionally, both climate change and the continuing rapid increase in population are expected to limit the rate of future mortality reduction. A complex and multifaceted relationship exists between population pressures, climate change, and child health. Because these aspects interlink in unique and often poorly understood ways, the exploration of this topic can easily become misdirected and overwhelming. Relationships are also confounded by social, economic, and geographical contexts, exemplified by considering two children from vastly different socio-economic-geographical backgrounds who both face the implications of overpopulation. A child who lives in an environment with poor access to healthcare, limited economic opportunities, and a governmental/political system limiting her ability to live healthily will be at a much greater risk of overpopulation-associated issues, such as malnutrition and decreased food security. Conversely, a child living in a country with greater socio-economic-health opportunities will be better equipped to deal with the pressures of a high-population and climate-disrupted future.

The literature on overpopulation and child health can be broadly categorized into (*i*) direct impacts, (*ii*) indirect impacts, and (*iii*) examination of physical and behavioral changes resulting from child-health status (Figure 6). Direct impacts of overpopulation on child health include the ways in which overpopulation exacerbates food insecurity, malnutrition, and therefore, poor health outcomes. The indirect impacts include more varied mechanisms often concerned with how overpopulation drives climate change that impedes child health. The ecological footprint concept (41) demonstrates that the combination of population and consumption outstrip the planet's ability to sustain our collective behavior. Based on United Nations data from 2005 to 2007, approximately 800 million people globally are undernourished, and food requirements will need to increase by 40% by 2030 and 70% by 2050 to maintain this proportion of malnourishment (184). But food security is threatened by an increasing population straining vulnerable food-supply systems and by a changing climate damaging and limiting food production itself

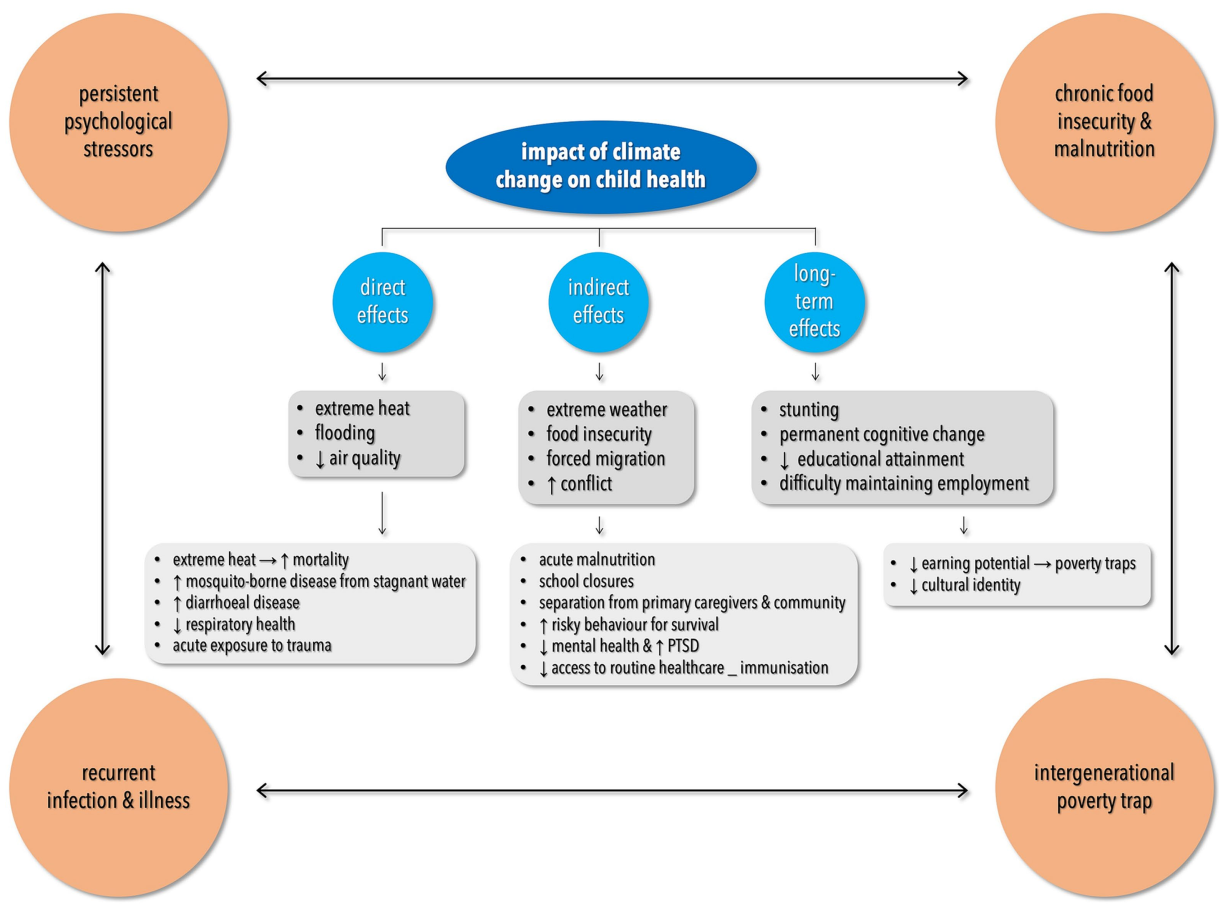

FIGURE 6
Climate change has direct, indirect, and long-term impacts on child health that are influenced by socio-economic and geographical conditions. Adapted with permission from Wiley (Ref. 183), © 2021 Paediatrics and Child Health Division (The Royal Australasian College of Physicians), https://doi.org/10.1111/jpc.15704.

(185, 186). The geographical distribution of the Earth's undernourished population is mainly in Asia (381 million undernourished) and Africa (250 million undernourished) (8) where overpopulation exacerbates the problem (187) and is centered on large nuclear families. Having limited economic resources in large families reduces nutrition and healthcare in children (187); therefore, overpopulation threatens child health by placing strain on economic resources.

Poor food security that begets malnutrition is not only underscored by limited economic capacity, but also by threats to the food-supply network, with climate change being one of the greatest threats operating mainly via increasing drought (186). Data based on the approximately 20% of malnourished children aged <5 years old in northern Kenya demonstrate that drought raises this percentage incrementally (188). In Ethiopia, a 1°C rise in average prenatal temperature was associated with a 28% increase in the odds of severe stunting in early life (189). Temperature increases can reduce crop yields, thereby restricting nutrition including for many pregnant women, resulting in lower birth-weight offspring and an increased prevalence of stunting and child mortality (190). In the Ethiopian context, an exception to this phenomenon exists in the cooler highlands, where a temperature increase often decreases frost damage to crops and consequently increases food security (189). Climate change alters other aspects of weather systems beyond drought. In Indonesia, a 40-day delay in the monsoon can reduce rice yield by 6.5–11% (191), while a 44-day delay led to a 6.3% decline in mean height-for-age in children (192). Such accumulative, short-term disruptions translate to losses in long-term nutritional status, regardless of the local region's ability to recover from such an event.

Climate change affects almost every aspect of our environment, and so also affects human physiology and health, with children being one of the most vulnerable age groups (193). In fact, children will bear 88% of all health adverse consequences related to climate change given their unique physiological and behavioral characteristics, in addition to accumulated exposure (194). In New York, increased heat variability from climate change increased the prevalence of pediatric presentation to hospital (195). In the Northern Territory of Australia, temperature extremes lead to increased pneumonia presentations to hospital, especially for children (196). In both California (197) and Europe (198), heat is a risk factor for respiratory admissions, yet the causal mechanism is not well-understood. Extreme temperatures have also been associated with other undesirable health outcomes in children, namely low birth weight (199), stunting (189), low Apgar scores (200), and increased risk of stillbirth (201). Increasing humidity in wet seasons promotes transmission of respiratory infectious disease in both Brazil (202) and Indonesia (203).

Climate change-exacerbated air pollution threatens child health. Childhood exposure to oxidants (O_3 and NO_2) are associated with increased incidence of asthma and eczema (204), and early exposure to increased pollutant concentrations trigger atopic dermatitis in children (205). In Italy, a 10-grain m^{-3} rise in total aeroallergen concentration increased the risk of asthma presentation to hospital not only on the day of the event, but also 2 days afterwards (206). Bushfires are becoming more frequent due to climate change (186), producing air pollutants with detrimental health impacts. For example, a 1 $\mu g\, m^{-3}$ increase in the concentration of fire-related $PM_{2.5}$ is associated with a 2.17-g reduction in birth weight (207), and increases in fire-sourced air pollutants have been linked with increased risk of pregnancy loss (208).

Of the known effects of climate change on child health, preterm birth (209) is the best-described. Regions at the highest risk of preterm birth due to extreme heat are those with colder and drier climates (210). In Minnesota, USA, pregnant women exposed to a 7-day heatwave of >37°C faced greater risk of preterm birth (211). In China, pregnant women are at greatest risk of preterm delivery when exposed to extreme heat during the third trimester (212), and in Spain preterm birth risk increased up to 20% when maximum temperature exceeded the 90th percentile over the 2 days prior to delivery (213). Similar results abound in many other regions of the world—e.g., Belgium (214), Australia (215), and Israel (209). Thus, while overpopulation threatens child health directly, it also drives anthropogenic climate change that, in itself, degrades child health (216).

3.3.4 Maternal education

The effect of maternal education on human fertility is complicated and equivocal depending on which aspects of "education" are measured, and the scale of investigation. Within nations, there is evidence that higher female education lowers fertility; for example, in Nigeria each additional year of education reduced fertility by 0.26 births/woman on average, as well as increased the age at primiparity (217, 218). Likewise, data from Ethiopia, Kenya, Tanzania, and Zimbabwe revealed that fertility fell most, and birthing interval increased most, among women with secondary education from the 1970s to the 2000s (219).

At broader spatial scales (among-country), the influence of maternal education on fertility is more ambiguous. Based on Demographic and Health Survey data from 43 countries, increasing educational attainment correlated with lower fertilities (220). The most-accepted paradigm—based on ample time-series data from single countries; e.g., Brazil (221), Kenya (222), Bangladesh (223), India (224)—is that child mortality declines as a mother's years of education increases, thereby de-incentivizing families to have more children. However, a more recent study examining data for 64 low- and middle-income nations revealed that while child mortality was the strongest predictor of variation in fertility, female education attainment (years of education completed) did not provide any additional explanatory power (165). However, it remains unclear whether education, while providing increased autonomy, is most responsible for the reduction in fertility *per se* (222), instead of the ability to seek medical interventions, the socioeconomic impact of higher-income employment, or a high-income earning husband. While strongly correlated, the link might not be causal, with maternal education acting more as a proxy for socio-economic status and geographic area of residence (225).

3.3.5 Social and cultural influences

Fertility is sequential, time-limited, and non-reversible, with fertility rate varying as a function of *tempo* components (i.e., age at primiparity, birth intervals) and *quantum* (e.g., whether parents can afford a large family, name continuation, potential contribution to household economies) (226). Thus, several other dimensions dictate fertility trends beyond education, infant mortality, and access to family planning. For example, a study of 70 low- and middle-income countries with high-fertility clusters determined that while low female secondary education attainment, low contraceptive use, and high unmet need for family planning were partially responsible (152), it also identified high-fertility clusters in areas crossing country borders,

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suggesting an influence of local cultural values rather than country-specific family-planning policies (152). Urbanization itself has been linked to lower fertility, but the quality of modernization arising from urbanization (e.g., economic opportunities) is an important element modifying the expected relationship (227). Some cultures also emphasize sons over daughters. This can manifest as shorter birth intervals when the previous child was a daughter (228), or the higher likelihood of opting for a "replacement" birth following the death of a son compared to a daughter (229).

Governments also introduce policies that affect population growth. In 1978 in China, statisticians and economists determined that population growth had to be reduced to reach the aim of quadrupling the per-capita national income, thereby laying the foundation for the one-child policy (230). Despite reaching the goal of reduced population growth, the violation of human rights was abhorrent. Similar results might have been achieved through the provision of quality, non-coercive, culturally appropriate family-planning services. Conversely, other parts of the world are currently experiencing cultural and religious barriers undermining women's hard-won rights to exercise choice. In 2020, the USA reduced funding and access to family planning services (231, 232), and Russia has recently prioritized "population growth" as a top health priority (233). Hungary and Poland, two countries with a history of restricting women's rights under conservative governments (234, 235), have near-total bans on abortions, reducing access in recent years (236–238).

3.4 Concerns about aging and declining populations

3.4.1 Population decline

Concerns (239–242) about population decline are rooted primarily in fears of an associated economic decline, with a potential reduction in gross domestic product a commonly used argument. Here, a population decline is assumed to lower the number of working adults, subsequently lowering productivity, and thus lowering national gross domestic product. The arguments against the validity of brute measures of market activity as reasonable indices of national wealth notwithstanding (243), a decline in gross domestic product is proposed to reduce innovation and lead to economic and fiscal challenges; indeed, traditional economic thought sees population growth as a major source of economic growth (241, 244). Lower growth of gross domestic production might also be driven by a reduction in domestic consumption as older people are thought to purchase fewer consumer durables than younger people. Another identified concern ensuing from low economic growth is a shift in geopolitical power as currently, higher gross domestic product is associated with higher geopolitical power. Other potential issues of a declining population include complexities in fiscal policies such as national health insurance and social security (245). Fears surround a contracting working population being burdened by an expanding aging population (246).

These concerns ignore existing evidence regarding the many economic and wellbeing advantages of smaller populations. First, the fear of population decline ignores that none of the existing population projections (see section 3.1.1) predict a decline in the global population (7, 13, 14). The global population is still growing (Figure 1), so the possibility of a "population collapse" over the coming century is nil. Second, stated concerns inherently assume a reduction in gross domestic product is a negative outcome, yet economic models show this indicator does not necessarily measure wellbeing, either for individuals or the planet (247). Continued growth in gross domestic product is an unconstrained, capitalist, pro-growth view that is not sustainable. Neither do lower fertility rates themselves imply lower economic growth. In fact, reduced fertility can increase capital per worker and per-capita consumption provided by human capital investments (248, 249). Lower fertility rates are also proposed to increase income *per capita* and lower carbon emissions through changes in total population size, age structure, and economic output (250). Assumed negative impacts also make unsupported assumptions about the continuation of past productivity trends, which are themselves mitigated by developments in technology. It is therefore difficult to quantify the potential effect of technology on future economic growth, because technology can also buffer change via low-cost labor supply (251).

More importantly, lower populations provide environmental advantages. Indeed, the available evidence shows that only 25% of the increase in greenhouse-gas emissions globally is attributable to per-capita increases in consumption, whereas 75% is due to population growth (252, 253). However, the IPCC Climate Change Synthesis Report Summary for Policymakers (1) does not mention population growth as a major diver of climate change. A decrease in population growth would reduce global emissions provided that consumption decreases at a comparable rate in the short term, but should promote large emission reductions in the long term. If the unmet need for family planning was filled, global emissions could be reduced by an estimated 0.7–1.25 Gt of carbon year^{-1}, or approximately 8–15% of the reduction in emissions needed to avoid warming of >2°C by 2050 (254–256). Based on projections from the United Nations 2004 World Population Prospects (7.4, 8.9, and 10.6 billion by 2050 for the low, medium, and high scenarios, and 5.5, 9.1, and 14.0 billion by 2100, respectively) (257), the low-growth path would reduce emissions by 1.4 Gt year^{-1} by 2050 (−15%) and 5.1 Gt year^{-1} by 2100 (−40%) compared to the medium path (258). In contrast, the high-growth path would increase global emissions by 1.7 Gt year^{-1} by 2050 (+17%) and 7.3 Gt year^{-1} by 2100 (+60%) compared to the medium path (258). While many assumptions underlie these estimates (e.g., economic growth trends, technological shifts, energy transitions, population structure, urbanization), they do not take resource constraints or environmental degradation limiting population growth into account (257). For example, urbanization alone is expected to increase projected emissions by >25%, especially in the case of developing regions (259). However, urban living is more energy efficient than rural living after controlling for income, which can cause a net decrease in emissions (259). Additionally, rapid urbanization can hasten the transition to cleaner fuels (260, 261).

Alternatively, population growth is potentially disadvantageous to a country's economy if it cannot keep up with the rising number of people to employ youth productively (262). For example, Angola's population growth rate of 3% year^{-1} since 1970 increased the population of 6 million to 33 million today—one of the world's highest rates of annual population growth (263, 264). Accompanying this growth is its poverty rate that increased by 15% between 2008 and 2018 (265). Angola's youth today suffer from poor living standards that its government and economy are unable to alleviate (266).

Even those economists purporting "profound social and economic implications" (246) state that the transition to older societies in a few countries (e.g., Japan) is "manageable" via structural reforms, technological advances, and debt stabilization. No financial "crisis" is on the horizon, but there will be a requirement to adjust existing fiscal policies, including to health systems and retirement funding (245). Furthermore, such adjustments are entirely realistic in the low-corruption, high rule-of-law countries where aging populations are of concern.

In conclusion, a downward trajectory of fertility and population growth rates is in our collective interest. There is no evidence that a lower population growth rate is necessarily detrimental to an economy.

3.4.2 Aging populations

A rise in the global aging population is another argument raised to promote population growth. The concerns mirror those stated for population declines: labor shortages, increased government expenditure in health care and pension funds, and reduced consumption—all culminating in economic decline (239–242). Labor shortages are feared to drive up prices and lower living standards. The proportion of persons aged ≥65 years globally is indeed projected to rise from 10% in 2022 to 16% in 2050 (7). This changing age structure will create some demographic challenges, as existing economic and fiscal policies will need to be restructured, but these are not unsolvable; further, increasing fertility rates, commonly proposed as a solution, will only worsen the problem.

The most commonly used variant of the dependency ratio—defined as the ratio of the number of people aged ≥65 to the number people aged 15–64, is projected to increase from 16% in 2019 to 28% in 2050 (267). But this 75% increase can be misleading because it does not fully represent the number of "dependents" relative to the working population. First, workforce participation of people ≥65 years has been increasing in countries with an aging population such as USA and Japan, especially in those with the highest number of years of education (268, 269). Second, people aged ≥65 are not necessarily economically dependent. Volunteering in old age is a sizable economic sector; a study in Canada proposed that even with conservative estimates of hourly wage, the sector was worth 2 billion US dollars in 2008 (270). Third, ignoring the cost savings associated with fewer children <15 years old artificially inflates the dependency ratio (271).

Fears of an associated economic decline are unsubstantiated; investing in the health, training, and education of workers—especially older, experienced workers—in fact increases human capital, effectively making the workforce more productive (245). Concerns regarding labor shortages are also unfounded. There is no basis for an expected penury of working-age people for countries experiencing low population growth or even decline—the question reverts instead to inadequate immigration policies that limit or deny the movement of capable, working-age people from elsewhere to fill local demand. But if immigration is used to increase population growth *per se* (*cf.* fill labor vacancies), the concomitant increase in resource use and emissions resulting from immigrants increasing their *per capita* consumption rates upon successful migration to higher-income nations (271, 272) contribute to growing environmental damage.

While there will inevitably be economic and fiscal challenges accompanying aging populations (245, 246), their solutions rely more on wise policy responses, such as redesigning pension financing, investing in education to enlarge the effective workforce, and a delayed retirement age to promote higher income taxes, which subsequently improves healthcare (245). It is telling that few academic papers provide support for envisaged catastrophic consequences of population decline and aging populations (241); almost all papers in the field acknowledge existing policy implementations that successfully address these challenges. Unfortunately, misinformed and alarmist arguments against a sustainable global population remain mainstream tropes (240).

4 Discussion

4.1 Avoiding the risks associated with overpopulation

After discussing the risks associated with high population size and the reasons why the global population has already overshot the planet's carrying capacity, we come to our central question: how do we prevent the worst-case scenario from occurring? First, we must consider our current economic model and its role in determining sustainable pathways forward.

The vicious cycle of population increase exacerbated by anthropogenic climate change, leading to even more climate change, and population growth, is a phenomenon not experienced equally globally. For example, the impact of climate change on food systems will affect everyone, but disadvantaged groups such as women, older adults, children and women in low-income households, Indigenous peoples, minorities, and smallholders, will be disproportionately burdened with malnutrition, livelihood loss, and rising costs exacerbating the cycle of existing inequalities (2). The principal drivers of anthropogenic climate change are also unequal—half of consumption-related emissions are generated by only 10% of people globally (273). Children are the most affected group, yet are not autonomous and must rely on the actions of adults, so it is incumbent on us to be their voice and protect their future.

Fulfilling a "safe and just space for all" (247) therefore requires empowering women, improving health and wellbeing for women and their children, and increasing economic prosperity (247)—actions that conveniently all lower fertility rates (274). Falling fertility is indicative of economic development, with delayed childbirth and fewer children consequences of education and career goals, and because of increased access to family planning. In many ways, lower fertility rates observed in developed countries are an indicator of female autonomy, empowerment, and equity. But women in low- and middle-income countries face multiple barriers to family-planning needs, as do an increasing number of women in high-income countries when laws and politics encroach on individual options. While the direct causality of education and fertility is unclear (275) (see section 3.3.4), there is a strong relationship between the years of maternal schooling and the probability of her children surviving (276–278). Given the most important, broad-scale determinant of reduced fertility is lower child mortality (165), the benefits are clear.

Improving women's rights positively affects economic development (279, 280); therefore, addressing social and economic disparities are essential actions for nations to create a more just future. Indeed, the *Global Burden of Diseases Study 2019* found overwhelming evidence that social and economic development is highly correlated with positive health outcomes, and proposed prioritization to improve the status of women, expanding access to education, and stimulating economic growth through policies and strategies (281). Put simply, a healthy population is a productive population; increasing access to education accumulates human capital and improves productivity. Improving the status of women kick-starts the process of human-capital accumulation, because maternal education both directly and indirectly affects their children's educational attainment (282, 283).

Persistently low fertility in high-income nations cannot be attributed solely to economic stressors, unemployment, lack of progressive public policies, or popular trends (e.g., postponing reproduction) (226, 284), because the phenomenon has persisted for too long and become a structural aspect of the developed world (244). For example, the demographic transition that occurred in Europe led to greater reproductive efficiency, meaning that before the transition, women spent ~70% of their adult lives bearing and rearing children (285). The corollary was that post-transition, women were massively liberated from "wasting investments" on children who ultimately died (286). Sustained high fertility and rapid population growth therefore impede sustainable development, counter to policies adopted by some countries such as Russia to prioritize population growth (233).

Policy discussions regarding overpopulation are beset by ideologies that underlie competing perspectives (287–289). Many governments attempt to boost their economic and political advantage by promoting population growth to overwhelm their less-populous neighbors (287), and there exists an unquestioned "wisdom" that has evolved over the course of human evolution that more people equates to doing better, because it meant more food, more capability, and better defenses (290). In contrast, rapid and unsustainable population growth hinders nation-level development, with China's one-child policy an extreme example of a country limiting population growth to boost economic development (291). There has been a long-held consensus that incorporating policies and programs to reduce high fertility in developing countries is a pathway to economic development (292–294). Many have also labeled those who identify population growth as an existential challenge as "racist" and socially irresponsible for "blaming" low-income nations for overpopulation (295–297); hence, there is a reticence to engage in emotionally charged debates on the topic (287, 289). Constructive discussion on overpopulation is further inhibited because of concerns of perceived "population control" related to past abuses arising from autocratic measures to limit fertility. Providing women and men the opportunity to determine their family size free of any form of coercion cannot be deemed "population control"—rather, it is an important human right that has been neglected. In particular, empowering women—especially disadvantaged women—to make decisions about when and how many children they have, will have positive impacts on their lives and the lives of their children, and is a proven path to development.

5 Conclusion

The many benefits associated with lower population growth and size are unassailable, especially given the necessity of mitigating the severity of climate change over the coming centuries. But achieving "optimal" human population sizes will require major social changes that are embedded within appropriate social-cultural-ecological contexts while simultaneously respecting planetary boundaries (39, 298, 299). While we conclude that smaller human populations benefit the most people, we emphasize that we are not advocating an end to childbirth. Rather, we join the globally progressive voice of promoting the empowerment of girls and women worldwide through ethical and practical solutions to determining their own fertility. Unfortunately, neocolonial attitudes still obfuscate the links between population and environmental degradation in low- and middle-income nations, so traction for quality family planning in these fastest-growing regions has stalled. We also emphasize that determining family size should not be left to women alone; men also need to be educated adequately and provided with contraceptive options to allow them to promote prosperous and just outcomes for their family. The problems of overpopulation we outline here will not be addressed entirely through family planning and education, as beneficial as these are. Working to increase child health and implementing policies that addresses food security and climate change will also help to reduce population growth further, bringing about many corollary benefits to human societies.

Author contributions

CS: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. MJ: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. LW: Data curation, Investigation, Resources, Writing – review & editing. QB: Resources, Validation, Writing – review & editing. NP: Methodology, Validation, Writing – review & editing. PS: Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Writing – original draft, Writing – review & editing. CB: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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Promoting community health and climate justice co-benefits: insights from a rural and remote island climate planning process

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Climate change is an environmental crisis, a health crisis, a socio-political and an economic crisis that illuminates the ways in which our human-environment relationships are arriving at crucial tipping points. Through these relational axes, social structures, and institutional practices, patterns of inequity are produced, wherein climate change disproportionately impacts several priority populations, including rural and remote communities. To make evidence-based change, it is important that engagements with climate change are informed by data that convey the nuance of various living realities and forms of knowledge; decisions are rooted in the social, structural, and ecological determinants of health; and an intersectional lens informs the research to action cycle. Our team applied theory- and equity-driven conceptualizations of data to our work with the community on Cortes Island—a remote island in the northern end of the Salish Sea in British Columbia, Canada—to aid their climate change adaptation and mitigation planning. This work was completed in five iterative stages which were informed by community-identified needs and preferences, including: An environmental scan, informal scoping interviews, attending a community forum, a scoping review, and co-development of questions for a community survey to guide the development of the Island's climate change adaptation and mitigation plan. Through this community-led collaboration we learned about the importance of ground truthing data inaccuracies and quantitative data gaps through community consultation; shifting planning focus from deficit to strengths- and asset-based engagement; responding to the needs of the community when working collaboratively across academic and community contexts; and, foregrounding the importance of, and relationship to, place when doing community engagement work. This suite of practices illuminates the integrative solution-oriented thinking needed to address complex and intersecting issues of climate change and community health.

KEYWORDS

climate change, community planning, health, rural, co-benefits, data equity

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1 Introduction

The Intergovernmental Panel for Climate Change (IPCC) states that climate change is producing myriad direct and indirect adverse health impacts, from increased morbidity and mortality rates due to acute trauma and disease emergences and amplification in human and animal populations through to mental health issues arising from significant climate events and their sequalae such as displacement, social and economic losses, malnutrition and food insecurity (1, 2). These effects are disproportionately felt by children, older adults, those who are structurally marginalized and those who live close to the land, such as Indigenous peoples (3–5). With each season where climactic records are broken and climate disasters occur in quick succession, people come to understand that climate change is not a distant future challenge but a present-day reality. For example, in British Columbia (BC), the wildfires, floods and heatwaves experienced in 2021 have shifted climate change narratives from a focus on projected impacts to current and urgent conditions to be addressed (6). The impacts of climate events and community responses to them are diverse and require careful consideration.

It is important that social narratives about climate change are informed by data that reflects the nuances of various ways and forms of knowledge; roots an understanding of issues in the social, structural, and ecological determinants of health; and takes an intersectional lens in understanding how social, political, and economic structures impact people's diverse experiences. The BC Assembly of First Nations, in their BC First Nations Climate Strategy and Action Plan, for example, highlights both cross cutting and community specific climate risks that Indigenous Peoples experience due to the ongoing impacts of settler colonialism and capitalism. This work identifies that the long term effects of initial and ongoing land dispossession and assimilation policies pursued by the Canadian State since colonization has impacted where Indigenous Peoples live, their socio-economic conditions, and how connection and relationship to Mother Earth is exercised, experienced and respected (7). Broadly, we concur with the importance of rooting climate change responses in data on the social and ecological determinants of health that is equity-informed. We link these data equity commitments to the importance of grounding work in place given the richness of insights gained during the community-led climate change work we conducted on Cortes Island, BC, Canada.

When working on issues of equity, we also emphasize the importance of engaging in reflexive practice and making explicit our positionalities, social locations, biases, and influences as they relate to research, practice, adaptation and mitigation and broadly reflecting on the social and material environments we occupy (8, 9). The co-authors of this article make up a diverse group of activists, community-engaged researchers, and educators, with five out of seven authors growing up on, or currently living on, Cortes Island. Members of our group have spent various years engaging in critical thinking about issues of equity-oriented data science, with disciplinary backgrounds spanning health sciences, public health, education, anthropology, sociology, environmental management, and geography. Our focus on interactions within socio-ecological systems is intended to help us understand the links between social systems and ecosystems (10). In acknowledging how social, economic and ecological systems are connected, we can then work to consider how future changes and adaptations may affect communities. It is through these lenses that we are sharing insights from our collaborative community-informed work on climate change planning on Cortes Island.

2 Context

Cortes Island is located in the Discovery Islands Archipelago, situated between Vancouver Island and the British Columbia Mainland in the northern reaches of the Salish Sea (see Figure 1). This 25 km long island (130km^2) is the unceded traditional land of the Coast Salish First Nations, specifically the toq qaymɩx^{W} (Klahoose), ʔop qaymɩx^{W} (Homalco), and ɬəʔamɛn qaymɩx^{W} (Tla'amin) Nations. Cortes Island has roughly 1,000 permanent residents, and a median household income that is approximately $30,000 less than BC's average (11).

Rural and remote island and coastal communities, such as Cortes Island, are disproportionately impacted by climate change. Cortes Island is accessible only by float plane, boat or ferry, yielding vast carbon emissions due to the transportation of people, goods and services, all of which can be easily disrupted during climate events. Despite unreliable and cost prohibitive access to basic goods and services, islanders have limited access to provincial and federal government services. For example, extreme weather events can impact access to healthcare on Cortes Island as the closest hospital is located two ferry rides away in Campbell River. A low median household income, limited housing stock and a higher cost of healthy foods pose significant challenges for Cortes Island residents who are already contending with myriad intersecting issues such as high rates of child poverty, increasing extreme weather patterns (e.g., droughts and heatwaves) and related climate change impacts to housing and food security (e.g., shellfish impacted by ocean acidification and intertidal species casualties from heatwaves and fires) (11–14). While considerations of intersecting social dimensions of health are often lacking from community planning processes and datasets, in communities like Cortes Island it is crucial to view community conditions through an integrative and holistic lens. Without community input, the development of community plans, policies and processes that are informed purely by quantitative data can be misleading and reduce effective short-, medium- and long-term planning. In response, our work was rooted in the premise that when considering what "effective" climate change adaptation for Cortes Island would look like, solutions must be grounded in community knowledge and perspectives, work at both the individual and community levels, and actively engage with the eco-social contexts within which climate change experiences and responses are rooted.

3 Methodology

This project was built through a partnership created between the Research for Eco-Social and Equitable Transformation (RESET) Lab at Simon Fraser University and the Friends of Cortes Island (FOCI) Society with the aim to gather data and formulate a survey to inform the island's climate mitigation and adaptation planning process. This partnership emerged from a need identified by the community (through FOCI) for mitigation and adaptation planning at the

FIGURE 1
Position of cortes island within british columbia (left) and map of cortes island (right).

community level. FOCI contacted the PI of the RESET Lab, to support this work. As the PI and several members of the research team either grew up on or currently live on Cortes also, we bring a unique insider/outsider perspective and positionality to our work together (15).

Our work for Cortes Island's climate planning process took place in five phases from May 2022 to August 2023. Phase 1: This partnered work began with an environmental scan of existing environmental and person-centered data about Cortes Island [see Supplementary material (Datasets Identified in Environmental Scan) for a summary of which datasets were included] (16). Phase 2: The next step of our partnership led to five informal scoping-related interviews with community members about their knowledge and expertise related to the assets on the island that were not represented in the data captured in the environmental scan, such as wetlands and old growth forest ecosystems (17). Throughout this project, we engaged in an integrated knowledge translation (iKT) framework, where outputs were given back to the community throughout the process of the work together (18). For example, during this stage of the project, a drought report, a community asset report, and an information sheet on heat-pumps was developed for the community. These outputs were requested by FOCI and were based off the environmental scan and informal community scoping interviews we conducted. Phase 3: In the third stage of the project, we attended a community planning forum for the social profit sector (19), where we participated in a climate change focus group that the Island was running with six community organizers about mitigation and adaptation to climate change events on Cortes Island. During this gathering it became evident that the community's climate adaptation planning process would benefit from a synthesis about existing guidance on justice-informed community engagement strategies (20). Phase 4: After this gathering, we conducted a scoping review of peer-reviewed and gray literature asking how recognitional, procedural, and distributive justice can be used as a lens for progressing community engagement in local climate planning processes. Search terms, databases, and PRISMA chart of papers can be found in Supplementary material (PRISMA Chart of Scoping Review and Search Strategy, Terms, and Databases from Scoping Review). We recommended a distributive, procedural, and recognitional justice lens to FOCI as a way to inform future community engagement activities that will be used in climate planning given their utility when used in different rural and remote contexts. Documents were included based on three key factors: (1) utilizing a place-based context to climate change mitigation and adaptation, (2) inclusion of procedural, recognitional and distributive justice and (3) best practices for community participation in planning. In total, 33 climate adaptation resources met these criteria and were included and developed into a community engagement report. Phase 5: The findings from this review and insights from the aforementioned phases were then applied to the development of a Cortes Island survey for residents about climate change planning on the island. More specifically, the scoping review, community interviews, observations from the focus group, and environmental scan informed which questions were asked, the phrasing of the questions, and our dissemination strategy for the community survey [questions can be found in the Supplementary material (Draft Survey Questions Informed by Scoping Review)].

This paper brings together reflections from our team of researchers and community members on lessons learned from each step of the partnership and project development. Each phase of our project was iterative and led to the development of the next steps, clarified areas of focus, and aided in the development of deliverables. This paper is not intended to summarize in detail the findings from each of the five phases of work, but rather, to offer insights into the lessons learned from working together across the life course of this project and within a university-remote community partnership.

3.1 Framework

Rooting data science in theoretical frameworks, in our case in eco-social and critical theory, promotes the meaningful development of research programs which pay careful attention to the epistemological, ontological and empirical orientations central to the program of research.

In this study, we rooted our approach to research and partnership development in eco-social approaches to health, critical data studies and critical place inquiry. Eco-social approaches to health acknowledge "the reciprocity among the ecological and the social as essential features of a proactive orientation to future health and collective well-being, especially in the face of rapid planetary-scale ecological changes that threaten human well-being and societal stability" (21) (p. 61). Eco-social approaches to health highlight the role of relationships and interconnections between ecological and social systems (and challenge constructed dichotomies between the two) thus taking an orientation that pays homage to Indigenous knowledges and epistemologies (21). Using an eco-social approach to health also led us to engage with social and environmental determinants of health, with a specific interest in how the local level was reflected in the datasets. This material was included in the environmental scan, informed the development of the questions that were asked of community and the information that was deemed relevant in the asset mapping, and the posing of the justice question that guided the development of the community engagement report. This public health orientation to engaging in climate change planning, extends from calls from Parkes et al. (20) and Hancock (22) to utilize an eco-social approach in public health to address climate change.

Rooting our data science approaches in equity-driven and critical theoretical frameworks, such as critical data studies, acknowledges that data and how they are analyzed, are not neutral categories and processes (23–25). Rather, data also always represents people, places, structures and relationships and thus are contextual, relational, and situated in place-based settings (25, 26). Grounding data considerations in principles of critical place inquiry centers the need to develop research methods that account for meaningful considerations of both place and social positions (27). Data and science rooted in Western philosophy and capitalism bakes into its logic a dualism between humans and nature (28). To correct for these ontological biases, we have sought to ground our work in place—not conceived of as a static material context but rather as a living space, a place of social reproduction, ecological unfolding and a dynamic set of interrelationships that change over time and through the interplay between people, species, and social practices (27, 29, 30). Further, critical place inquiry urges us to notice how social locations and realities influence how people experience "place," and also how they understand and influence these contexts (27). Place is not only a social construct, but also refers to the very land, water, air and mountains that constitute these places. Less seemingly permanent characteristics, such as flora, fauna and even weather patterns, also interrelated to produce a specific place at a particular time (27). With this lens, researchers must center (rather than keep peripheral or secondary) commitments to Indigenous sovereignty, the non-abstraction of nature, and the value of Indigenous epistemologies in relation to the fundamental ideas that land and water are life (27, 29).

One way that theory meets practice is in the very structuring of the research process, including the questions that we ask of ourselves and one another. Within the context of our work on community climate change adaptation and mitigation research, policy and practice, productive questions include: What counts as 'data'? Who is represented and who is missing in existing data? Why do these gaps exist? How can we effectively integrate social, environmental and climate data to tell a story of interaction? Who has access to existing data and who has the knowledge to use them meaningfully? How do we bring in more-than-human needs and experiences to data? What do we need to enact to avoid using data in stigmatizing or exploitative ways? What are the limitations of standardized data when working with rural and remote communities and on eco-social phenomena? Who needs to be involved in the selection of relevant data? How far can the findings from data bring us without ground-truthing them in place and local experience? How can data be used to identify a community's assets and strengths? In other words, how can we move away from treasuring what we can (easily) measure and rather learn to measure what we treasure?

Climate change, among many of the complex problems we face at the intersection of health and environment, are fundamentally equity issues (31–34). Given that climate change impacts—when assessed through a holistic lens—span social, health, political and economic sectors, it remains important to understand the intersections between climate change and social, environmental, ecological and planetary Determinants of Health (DoH) across scales of individual, community, and eco-social systems (4). Therefore, we argue that issues of climate change and environmental health benefit from grounding data collection, analysis, and reporting in critical place inquiry wherein place-based and disaggregated data can be produced and analyzed through reflexive and equity informed practices. These complex data are suited for the task of unpacking and concretely addressing the complex issues we are facing, including 'wicked problems' such as climate change and zoonotic pandemics which emerge out of contexts of social and environmental degradation. Additionally, it is crucial to link these phenomena with the structural and systemic layers of marginalization and oppression which exist. Therefore, when working on issues that intersect community and environmental health, we must acknowledge the impact that colonial and capitalist structures have had on our conceptualizations of 'environment', 'community' and 'health'. A clear example being, how water is commonly talked about in policies and practices as a hazard, resource and access to it as a human right, rather than as an entity worthy of rights itself and as a source of life through which human societies are intertwined in networks of reciprocity, accountability and responsibility (35).

4 Results from the five phases

4.1 Phase 1: environmental scan

The results of our environmental scan illustrated that there were significant, and in some cases, irreconcilable differences between regional district and census data and the living realities of island residents. For example, existing data about Cortes Island prior to 2022 identified that less than 5% of homes on Cortes Island need repairs, 75% of the residents are homeowners, the majority of residents are food secure, and that roads are suitable for biking (16). However, through discussion between FOCI, the research team (many of whom are community members themselves) and scoping conversations with residents, we learned that these findings were not representative of lived experience or existing services and infrastructure. For example, a large number of Cortesians struggle annually with housing quality, stock availability and affordability along with serious issues of food security. Further, mobility is a chronic problem for many as there is little public transportation infrastructure, fuel prices are high and many roads on Cortes Island are unpaved, steep, windy, unlit, and have deep potholes, and many Cortes Island residents speak about serious crashes occurring on-island. The findings from this environmental scan and the processes of ground truthing data with locals emphasizes the importance of community engagement in research and decision-making processes to not only improve data accuracy, but to also increase the likelihood that research and data can accurately inform the development of more equitable and appropriate planning and climate change processes. This is particularly true for research regarding rural, remote, Northern and Indigenous communities as much of Canada's existing climate change adaptation and mitigation efforts have been rooted within urban contexts, with a focus on infrastructure (i.e., public transportation electrification, mobility pricing, retrofitting) and larger scale populations that can be more easily characterized in standardized data gathering processes. Therefore, climate change planning must retain flexibility so efforts can be re-envisioned for applicability and equity in non-urban contexts, where infrastructure and key determinants of health such as public transportation, personal vehicles, food security, employment and housing are constrained.

However, despite its drawbacks and various data limitations, the Environmental Scan did illustrate various strengths and initiatives taking place on Cortes Island. Working in community contexts, it is important to acknowledge and name the agency, assets and activism of communities. For example, despite the aforementioned challenges facing Cortes, the Klahoose First Nation's Indigenous environmental leadership and actions include a range of initiatives, such as the development of a clean energy project, the investment of generators to protect local food harvests during power outages and the development of bivalve shellfish aquaculture as a key development of low-carbon futures, income, and food security. These initiatives center the vast Traditional Ecological Knowledge, which is not held by settler communities and help to build a future that is grounded in the communities, values, priorities and commitments to flourishing (16). Centering Indigenous voices and leadership in climate change adaptation and mitigation efforts, and drawing connections between the health of ecosystems and health of communities, is vital not only for Truth and Reconciliation but also for building sustainability, restoration and wellbeing into climate planning.

4.2 Phase 2: drought report, heat-pump resources and community asset report

Once it became clear the Environmental Scan of academic and gray literature did not provide an adequate understanding of social and ecological conditions on Cortes Island, the research team worked closely with FOCI to understand current issues facing the community related to climate change, education, and outreach. Themes of importance included the impacts of the Fall 2022 drought experienced on the island, energy and efficient heating (14) and mobilizing knowledge about existing eco-social assets such as the Children's Forest and the work of the Social Profit sector (17).

The next steps taken by partnership were to conduct five informal scoping interviews with community members about their knowledge and expertise related to the assets on the island that were not represented in the Environmental Scan. Cortes Island serves as a generative example of the power of diverse knowledges and experiences and illustrates how these knowledges can provide nuance and context to quantitative data. For example, the sister nations the Klahoose, the Tla'amin, and Homalco Nations hold knowledge built from living on their traditional territories for thousands of years. Knowledge is also shared from those whose knowledge has been built through generations of place based living on Cortes Island, from those across the life course—from children, young families, through to seniors and elders, and from professionals and academics, including marine biologists, mycologists, botanists, ecologists, geologists and wetland restoration experts. Children and youth growing up on the island also have a unique set of important insights to share. For example, wetlands and old growth rainforest ecosystems emerged as eco-social assets from our informal interviews (17). Local knowledge shared was gained through observations of environmental complexity derived from engaging with the system holistically, through relational heuristics and living experiences (17, 36). People shared information about local disaster risk management strategies, insights from the decades of data they collected in physical notebooks while monitoring salmon streams, and examples of the co-benefits of ecosystem restoration and wildfire management due to the Island's wetland restoration work.

Through these diverse epistemic lenses, the community helped us ground-truth existing data and begin to identify ways to fill gaps where data are missing. Relational heuristics, those localized observations made over time which are often transmitted through narrative stories or descriptions were also crucial. Thus, including a range of knowledge holders in data and knowledge production can address gaps in baseline data and place decontextualized knowledge back into place are two strategies that have helped to address significant impediments that had initially impacted the development of the Cortes Island resilience plan. By giving locals a chance to engage with local initiatives there is a greater likelihood that research and projects 'about and with' a community can be harnessed to create more meaningful change. As such, it is a disservice to view community engagement acts - such as consultation and learning from local and traditional ecological knowledge - as simply a matter of ethical behavior and responsibility. Rather, viewing the community as critical to research, we improve the integrity, accuracy, and utility of our data and increase research capacity to meaningfully and adequately address data gaps and community needs.

4.3 Phases 3–5: justice-informed community climate planning report and the social profit forum

After the environmental scan and community asset mapping process, our team conducted a scoping review of the literature describing community inclusion in local climate planning and shared our findings in a community report.

Our scoping review of the literature explored how, respectively, distributive, procedural and recognitional justice provide an approach to community engagement that retains attention to the envisioning and building of a collective future (37, 38). Distributive justice is concerned with how social, economic, and ecological goods are distributed as well as the impacts of climate change (37, 38). Participatory justice is concerned with who is included in the decision-making processes and how they are included in terms of power dynamics and role. Recognitional justice is concerned with who is acknowledged in terms of the impacts and often references intersectional identities (e.g., socioeconomic status, culture, gender identity) (37, 38). Therefore, in thinking about and actioning climate justice at the local level, engaging community members has been recognized as a robust starting point for cultivating climate justice (39).

Literature also highlights that local knowledge and a sense of place form the basis for meaningful community engagement within climate change planning processes. For example, Johnson et al. (39) state "notions of place attachment, sense of place, the role of culture, and sense-making in social discourse are increasingly being used to understand the complex interactions between society and the environment… and how societies respond and adapt to change" (40). The research also reminds that the impacts of climate change are felt across all scales, but at the local level the impacts will be unique to each community; therefore, it is important to consider how external drivers may affect the existence, sustainability and allocation of resources to the community (40). Community perspectives were sought in a variety of ways. For example, during the development of the community engagement report, a team member attended the Social Profit Forum where it was highlighted by the Social Profit Network (a network of social profits and nonprofits on Cortes), that community members on Cortes "face higher than average costs and lack of access to basic needs such as housing, transportation, healthy food, mental health support, education, laundry facilities, private childcare and insurance as compared to the average BC resident" (19, 41). Attending this gathering of local social service providers confirmed many of the inaccuracies in the Environmental Scan, and informed the development of a new suite of future community engagements activities that were presented to FOCI. The value of the capacity of the Social Profit Sector to convene cross cutting conversations on issues such as housing, climate change and poverty was clear as was their attention to power, representation and voice, for example by making conscious efforts to reflect on who is and is not in the room. To support this equity commitment, we shared recommendations from our review of community engagement literature which advocated for providing multiple mediums for engagement, including meeting in person and online and providing multiple mediums of information exchange, such as via surveys, meetings and gatherings. In a small remote community like Cortes Island, directly inviting members of the community, such as youth and the Klahoose First Nation, to participate is important in ensuring equitable participation. For complex topics such as climate change, it is important that processes are stewarded through strong facilitation which is rooted in an awareness of human and more than human health and wellbeing, cultural humility, solidarity, power and privilege, intergenerational inequalities, trauma- and healing-informed approaches and structural forms of marginalization (41, 42).

Our community report also recommended FOCI pursue scenario planning as a potential future activity as this method of community engagement is increasingly being used to create adaptation strategies for climate change that center justice (10, 40, 43). Scenario planning involves descriptions of various scenarios that have the potential to unfold within specific spaces, places and times and draw upon available science to promote decision making (40, 43). Scenario planning is particularly useful in exploring uncertainty as it allows for the integration of knowledge, interests and opinions as well as creates a process of community learning and dialogue with diverse community members (40). In addition to integrating elements of uncertainty, scenario planning allows for the integration of present and future assumptions and invites community members to come together to envision a range of collective futures (10) and to consider how to build pathways to these futures.

The findings from the community report were then drawn upon by FOCI and research team members to develop a Cortes Island survey to be administered to residents about climate change needs and priorities on the island. More specifically, this review informed which questions were asked, the phrasing of the questions, and our survey dissemination strategies. Questions were developed to reflect the value and goals of justice-oriented community climate planning and thus asked questions about: "*For what?*: How do we ground our thinking about the boundaries of systems that affect our lives in these types of processes?"; "*To what?*: How do we think about what the socio-ecological systems that we interact with are impacted by?"; "*For who?*: Who will our solutions benefit? What community assets exist that could be leveraged to build resilience to different climate futures?"; and "*Over what time frame?*: What timescale are we considering in our planning processes?"

5 Discussion

This project, conducted in part by 'insider/outsider' scholars, climate scholars, community organizers, and activists, draws lessons from engaging in a community-based climate planning process in a remote island community context and highlights the complexity of developing community climate plans that address data gaps, attend to social inequities and seek to build concrete climate action. This work also highlights tensions that arise when most data are deficit-based yet the literature advocates for centering the needs of the community, being responsive to place-based contexts and nuanced in an understanding of how health and wellbeing is produced in the nexus of social-ecological interactions. In this research, however, these core research insights dovetailed with community knowledges where residents drew from their understanding and experiences of living on Cortes Island where the social, economic and ecological experiences of living remotely and experiencing climate change on an island home are often directly felt. Thus, in alignment with existing literature, it is clear that through the experiences of community members we can understand local impacts of climate change, identify adaptive capacity and articulate how these intersect with local and regional contexts (41) and address issues of inequity arising within socio-ecological systems interactions (10). In acknowledging how social, economic and ecological systems are connected, we can then work to consider how future changes and adaptations may affect individuals within a community. Therefore, thinking at the local level about systems allows us to recognize links between different issues, which allows for co-benefits planning that seeks to address multiple community challenges (42).

Historically, top-down approaches to climate change mitigation and adaptation have created a stark division between citizens, science and policymakers, which have led to largely ineffective actions and limited buy-in (39). Without effective community engagement, power dynamics can define the boundaries of the socio-ecological systems in ways that serve a minority of perspectives and lead to inequitable solutions to community challenges (10). As is evident both in the available literature and our project's findings, acknowledging the value of local and traditional ecological knowledge is critical to supporting equity through data as the qualitative observations that inform them allow us to paint a fuller picture of health in the interplay between social, ecological and climatic processes, while also accounting for the cultural importance of species and places. Failing to do so runs the risk of using communities as a source for data extraction; studying them to further academic research without also addressing community concerns and taking local knowledge seriously, as well as running the risk of producing data which are erroneous, incomplete or biased. Community knowledge can also be empirically important, for instance, there is a lack of scientific literature on salmon spawning runs on Cortes Island; however, locals routinely collect data on streams and salmon-return data that may not be shared with/of interest to policy makers and government (e.g., the Friends of Cortes Island Society streamkeepers) (17).

Multiple members of our team hold insider-outsider roles as researchers, as community members and activists. As a part of our reflective practice on this project, we discussed the tensions that exist between community-relevant outputs and the types of work and ways of working that are valued by the scientific/academic community. Acknowledging the limitations and colonial structures which guide academic practices, our team engaged in ongoing reflection to ensure that the priorities of the communities remained central in this project. To put academic processes in service to community, we identified what skills and assets we have available to provide to community organizations, such as access to paywalled literature and experience conducting academic literature reviews and reports. For the researchers on our team, we often found ourselves questioning how to be in service to academia and our community at the same time. Thinking about the utility of our outputs and the contribution of the data we collected through academic literature, gray literature and informal interviews with the community was a humbling process for the early career researchers on our team who are also grappling with the complexity of both wicked issues such as climate change and how academia can be in service to community organizing and planning processes. Prioritizing integrated knowledge mobilization strategies was an important element of this work as well. As illustrated by the Canadian Institute for Health Research, "the central premise of iKT is that involving knowledge users as equal partners alongside researchers will lead to research that is more relevant to, and more likely to be useful to, the knowledge users" (44). Integrated knowledge translation calls for reflexive, ethical co-production of knowledge in academic spaces rooted in a critical analysis of power dynamics, which is a process members of the team discussed at every stage of the project and led to FOCI leading the informal interviews and holding the data as well as outputs oriented toward the community (45).

This project effectively remained iterative and responsive to community interests and needs, and showcased strategies for doing place-based work on climate action planning. Despite these strengths, this research has some limitations, including being less applicable to other settings given how focused our methods were on this particular community context, working with a small group of community organizations to set the foundational work for climate planning on the island, and moving beyond the bounds of what some may argue is the purview of classical climate resilience planning given the feedback loops between a range of intersecting structural issues, from housing and food insecurity to poverty and lack of community infrastructure.

6 Conclusion

In working toward equitable data approaches that enable us to measure what we treasure, we underscore the value of mixed-methods approaches such as the inclusion of community knowledges when working with quantitative data in order to uplift multiple ways of knowing and to meaningfully center these rich qualitative data in climate adaptation and mitigation planning. Our work with the Cortes Island community has highlighted the complexities of what counts as data, identified issues of quantitative data limitations and inaccuracies, and raised issues of how to increase justice-oriented community involvement. In developing the type of integrative solution-oriented thinking we need to address issues of climate change and community health, we found that the following is required: (1) collaborating across sectors and disciplines to measure, evaluate and monitor social, environmental, climate and health data; (2) building in mechanisms of researcher accountability to communities through the ground truthing of data with the people that these findings are about; (3) using stories of community challenges and successes to guide research; and, (4) revealing and advocating for filling silences in data collection by leveraging mixed-methods and integrating epistemic diversity into knowledge formation processes.

The immediacy of climate change mitigation and adaptation should not abdicate our responsibilities as researchers to address the inequities inherent in our systems of data collection, integration and analysis, which themselves are enmeshed in the colonial and capitalist epistemologies and structures that concurrently work to perpetuate and deepen the climate crisis. Our responsibilities extend beyond our human relations to the ecosystems within which our individual and community health is embedded and thus lead us to support taking a more than human approach to climate planning. This entails going upstream until it becomes clear that the ecosystems are our health systems, advocating to dismantle the silos within which we address community health and promoting an embrace of interventions that aspire to identifying co-benefits and engage in multisolving (35). We suggest that when applying the findings from this work to other communities' climate adaptation and mitigation planning processes, that the foci, phases, and processes be tailored to the specific social, ecological, and place-based contexts and community needs, assets, and interests of each place because while climate change is a global phenomenon it is experienced and responded to in the intimacy of our own lives, homes, neighborhoods and communities.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing. KT: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing - review & editing. FB-H: Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. SC: Data curation, Formal analysis, Writing – review & editing. MT: Conceptualization, Supervision, Validation, Writing – review & editing. MAG: Validation, Writing – review & editing. MKG: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1309186/full#supplementary-material

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A toxicological perspective on climate change and the exposome

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Climate change is accompanied by changes in the exposome, including increased heat, ground-level ozone, and other air pollutants, infectious agents, pollens, and psychosocial stress. These exposures alter the internal component of the exposome and account for some of the health effects of climate change. The adverse outcome pathways describe biological events leading to an unfavorable health outcome. In this perspective study, I propose to use this toxicological framework to better describe the biological steps linking a stressor associated with climate change to an adverse outcome. Such a framework also allows for better identification of possible interactions between stressors related to climate change and others, such as chemical pollution. More generally, I call for the incorporation of climate change as part of the exposome and for improved identification of the biological pathways involved in its health effects.

KEYWORDS

adverse outcome pathway, xenobiotics, heat, air pollution, hallmarks of diseases

Introduction

Health and wellbeing (Goal 3) and climate action (Goal 13) are 2 of the 17 sustainable development goals (SDGs) formulated and endorsed by the United Nations. A number of other SDGs refer to environmental quality. Despite the literature on human health and climate change building and evolving since at least 1989, the Conferences of the Parties (COPs) on climate change (henceforth CC) have barely mentioned health. However, during COP28 (held in December 2023), extensive discussions of the impact of CC on health took place. Indeed, health is mentioned in the draft statement: "Attaining resilience against climate change related health impacts, promoting climate-resilient health services, and significantly reducing climate-related morbidity and mortality, particularly in the most vulnerable communities".[1] A better understanding of the impact of CC on health and wellbeing is increasingly recognized as critical for public health. In this perspective article, the relevance of the exposome concept and toxicological tools to improve understanding of the relationship between CC and health is discussed.

Christopher Wild coined the term exposome in 2005 and defined it as the life-course environmental exposures from the prenatal period onward (1). These exposures include chemical, biological, and physical, as well as social inequalities and psychosocial influences. In that sense, the exposome is the complement of the genome (2). This definition was further developed by Rappaport and Smith, who highlighted the relevance of a thorough analytical

1 https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf

characterization of chemicals in body fluids. This corresponds to the internal component of the exposome, while environmental and behavioral factors correspond to the external components of the exposome (3). Miller and Jones included the biological impacts of exposures in their definition of the exposome (4). Consistent with this, it was recently suggested that toxicological tools could be useful for the characterization of the human exposome (5).

The effects of anthropogenic CC on human health correspond to an increasingly visible change in the exposome (6, 7). CC influences exposures to physical stressors (heat and UV), chemical stressors (ground-level ozone and particles), and biological stressors (vectors and the diseases they transmit, infectious agents in water, and pollens), as well as psychosocial stressors induced by extreme weather events (7). The exposome concept appears well suited to analyze these effects by incorporating all these stressors as well as their interactions (1). Furthermore, the "co-benefits" strategies for CC mitigation call for a holistic assessment of the attenuation of pollution sources (e.g., increased active transport has been suggested as reducing greenhouse gas emissions while also improving fitness) and are in line with the exposome concept (8, 9).

Several recent reviews have highlighted the relevance of toxicological tools and concepts for the assessment of exposome health effects (4, 5, 10). Indeed, toxicological studies are currently based on omics (large-scale data-rich studies), systems biology, predictive molecular tools, computational approaches, and the adverse outcome pathway (AOP) framework in addition to more traditional experimental approaches (11, 12). Furthermore, there is a growing interaction between toxicology, epidemiology, and exposure sciences that is critical for risk assessment. With this in mind, it is relevant to explore whether insights from toxicology can improve the understanding of the health effects of CC, including through an exposome "lens."

Altering the external component of the exposome

CC alters several forms of exposure (see Figure 1). CC impacts the amounts and distribution of several environmental factors, which may lead to biological and health outcomes. In order to analyze these effects, modifications in environmental stressors induced by CC in different matrices are discussed below. The two major matrices that are analyzed are air and water, and the contributions of factors modified by CC as well as those of other environmental determinants such as pollution are examined.

One of the consequences of CC is the increase in ground-level ozone (13–15). Ozone is produced from chemicals of natural- and human-derived origin, such as fossil fuel combustion. Ozone is a known pulmonary toxicant; its effects can combine with other air pollutants to increase the risk of lung diseases (16). A CC-associated increase in drought will also increase atmospheric particulate matter. There are significant differences in the nature of particles that increase with CC (dust, sand, and smoke from wildfires) as compared to traffic, and it is likely that such increases will have systemic human health effects (17). Dust and sand particles can bind a variety of chemicals, sometimes transporting them over long distances. Wildfires will also increase pollutants, with considerable effects (7). Pollens and allergens will also increase with CC, and this will impact a number of respiratory and other diseases (18). Pollens may interact with infectious agents and other air pollutants to exacerbate diseases. Air quality will be considerably altered by CC in many areas of the world, particularly those where drought is expected to increase. On the other hand, any substantial reduction in the combustion of coal and other fossil fuels (to slow the rate of CC) will act to counter such a deterioration in air quality. Several environmental factors that are modified by CC elicit biological events such as inflammation, oxidative stress, and immune dysregulation, ultimately leading to lung and other diseases.

The decrease in water availability and quality due to drought will lead to increased concentrations of chemicals for humans and other species (19). Another critical factor is the increasing number of extreme events and floods. These spread infectious agents as well as potentially toxic chemicals, degrading water and soil quality (20). Increased heat, another important CC effect, may alter the properties of chemicals to which people are exposed, including their solubility, persistence, and volatility (19). However, at this stage, it is difficult to draw a general conclusion about whether the effect of heat on chemical toxicity is negative or positive. Similarly, soil quality will depend on the physical and metabolic properties of chemical contaminants.

Changes in the internal component of the exposome: xenobiotic toxicokinetics

Changes in the external exposome can lead to changes in the internal exposome. The latter can also be modified if the absorption, distribution, metabolism, and elimination of exogenous chemicals (xenobiotics) are altered by CC. There is indirect evidence that this may be the case. The impact of CC may vary depending on the type of xenobiotics. Some xenobiotics, such as persistent organic pollutants (POPs), are not metabolized and are persistent in the body, while others are readily metabolized and eliminated. Concerning POPs, which are stored in human adipose cells (21), there are suggestions that global warming may contribute to increased obesity and thus increased storage capacity (22). Whether this could lead to increased health effects from these chemicals is unclear.

Xenobiotic metabolic pathways are influenced by changes in physiological states, which may be altered by CC. Xenobiotic metabolism and elimination are primarily dependent on the functional liver, gut, and kidney. Heat, especially when accompanied by dehydration, alters renal function and impairs other metabolic organs, leading to accumulated levels of toxins (23, 24). Another effect of CC may be an increased risk of hepatic infection and inflammation, potentially also harming xenobiotic metabolism (25).

The microbiome is also sensitive to CC possibly leading to modifications in the absorption of chemicals (26, 27).

Common health targets of chemicals and climate change-related stressors

Several health effects of CC arise from increased exposure to environmental pollutants. Examples of such health impacts are detailed below.

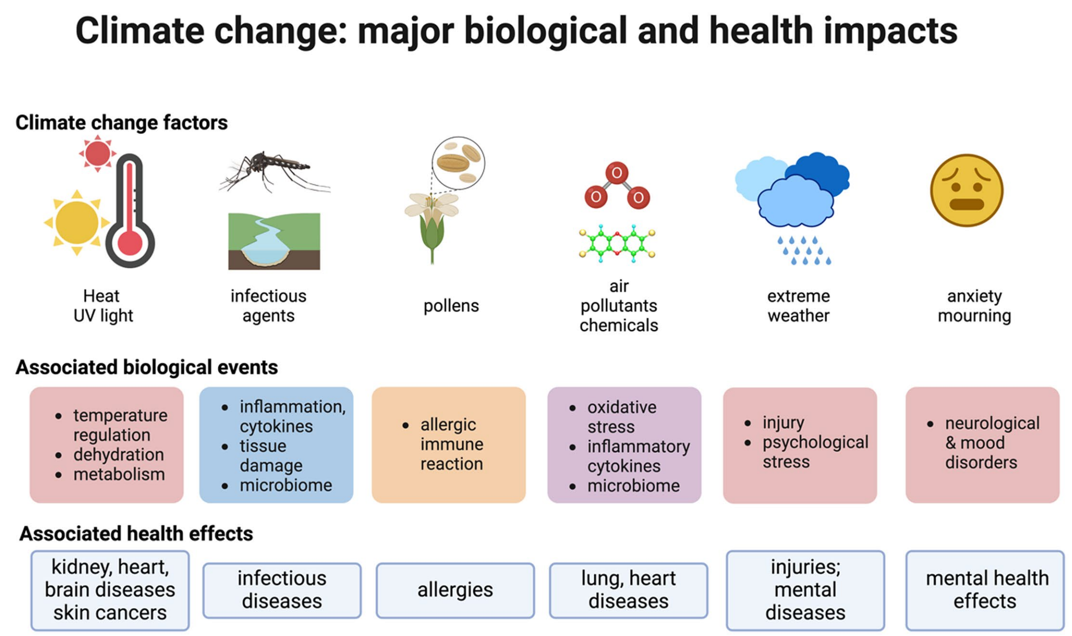

FIGURE 1
Climate change: major biological and health impacts. Climate change modifies a variety of environmental factors. These may interact with other stressors, thus altering a number of biological events and ultimately leading to health effects. The figure highlights key biological events as a first step in using the adverse outcome pathways framework. The figure was drawn with Biorender.

Immunotoxicity and infections

A hallmark of CC is an altered distribution (in some cases increased) of infectious diseases. This is due to changes in vector locations, accelerated life cycles of pathogens within some vectors, and pathogens contaminating water. Many chemicals have been shown to interfere with the immune system, leading in some cases to immunosuppression (28). This is in particular the case of dioxins and poly- and perfluoroalkyl substances (PFASs). Higher concentrations of PFAS correlate with decreased vaccination responses in children and an increased risk of infection (29). In the case of dioxin-like compounds, the mechanisms of immunotoxicity appear to be linked to the immune functions of the dioxin receptor (aryl hydrocarbon receptor), in particular in barrier organs (e.g., gut and skin) (30). Furthermore, both dioxin-like compounds and PFAS are highly persistent chemicals and will remain contaminants of high concern in the next decades, even if their global production is rapidly regulated (PFAS) or limited (dioxins). It is not proven yet that immunotoxicants will affect CC-associated infectious agents, but this is biologically plausible.

Neurotoxicity and climate change

Many chemicals have been proven to be likely or proven neurotoxicants (31, 32). The two main outcomes are developmental and adult neurotoxicity, in particular neurodegenerative diseases. There are several possible interactions between neurotoxicants and CC. Neuronal oxidative stress occurs in neurodegenerative diseases (33). Some of the health impacts of CC are also partly mediated by oxidative stress; thus, these consequences could be additive or synergistic. Furthermore, excessive heat and dehydration may also cause neurological harm. Further study of neurotoxins, including their interactions with infectious agents and air pollution that may also be altered in their risk profile due to CC, is of importance.

Mental health

It is now accepted that CC can lead to a range of mental health effects, including those resulting from exposure to extreme weather events (34). It is plausible that these conditions may interact with chemical exposure, aggravating or generating a variety of neurocognitive diseases, including among children.

Pulmonary and cardiac toxicity

Air pollution is generated by traffic, industry, and agriculture and is likely to be increased by CC (16). This eventually leads to lung and heart diseases. Importantly, heat also contributes to deleterious effects on these organs.

Reproductive health

Recent evidence has suggested that CC-associated pathways harm reproductive health, via means such as air pollution, exposure to wildfire, and excessive heat (35). Different mechanisms are involved, depending on the nature of the stressor. Many chemicals are also known to lead to reprotoxicity, in particular, endocrine disruptors (36, 37).

Cancer

An increased risk of cancer associated with CC is plausible because of increased exposure to UV and some chemicals via the pathways discussed above (9). The actual impact is, at this stage, difficult to assess. An increase in infectious agents could also lead to increased cancer.

These examples indicate that CC and chemical agents have common health impacts. It is still unclear if the interaction between these stressors is additive, synergistic, or otherwise. In some cases, interactions are biologically plausible (e.g., immunosuppressants and infectious agents), but in other cases, this remains speculative. An improved understanding of toxicology could help better characterize these interactions.

Relevance of new frameworks in toxicology to climate change impacts

In recent years, several new frameworks have been put forward in biomedical research, including toxicology. Among these, disease "hallmarks" (e.g., DNA integrity as an indicator of cancer) highlight major biological processes perturbed by illness (38, 39). Key characteristics are focused on the agents that can lead to an adverse outcome and are mostly used in the field of cancer (e.g., genotoxicants) (40). The characterization of AOPs is currently one of the major objectives in toxicology. An international effort has been launched to identify such pathways and publish them on a dedicated website, AOPwiki.[2] An AOP is a chain of linked biological events that begins with an identified molecular trigger, ultimately leading to an adverse outcome (41). Importantly, event–event relationships are evidence-based. Each of these frameworks is useful under certain conditions; they are complementary to a large extent.

Concerning CC and its possible interaction with other exposome factors, I argue that the AOP framework is relevant. It is noteworthy that AOPs are agnostic in that they are not specific to a stressor but rather can be triggered by a variety of them. A first step would be to identify biological events that link CC to health effects. This allows us to link biological events that are included in available AOPs to CC-related environmental stressors or prompt the development of additional AOPs. Furthermore, AOP networks, which illustrate how different AOPs share common events, can show how CC-related stressors interact with other stressors. For example, increased inflammatory cytokines can be key events in pathways triggered by CC-related stressors as well as by chemical contaminants (e.g., the key event n°1,496: "increased secretion of inflammatory mediators," AOPwiki) (see Figure 1). Oxidative stress is elicited by chemical, physical, and psychological stressors (42). Extreme heat is a physical stressor that leads to a variety of life-threatening outcomes and targets different organs including the kidney, heart, and brain (7). It initially leads to a loss of internal temperature control, which is then associated with different outcomes. Developing AOPs, including the dysregulation of body temperature control and ultimately leading to diverse health outcomes, would be useful to identify links to available AOPs and to infer possible interactions with other stressors.

In a previous commentary, we called for the application of the AOP framework to social hazards (43). Most of the effort in the field of AOPs has been accomplished by toxicologists using data primarily derived from studies on chemical hazards. However, since AOPs are agnostic by design, it should be possible to use the framework for a variety of stressors and conditions reflecting the universality of the concept. An advantage of such an approach is that it allows a better description of interactions between different types of stressor-elicited pathways (e.g., social and physical, CC, and chemical). We argued this should bridge different fields to the benefit of biomedical and environmental research.

Conclusion and recommendations

There is increasing knowledge of the impact of CC on human health; however, much remains unknown. Delineating the mechanistic pathways will help to identify and predict possible interactions between different stressors associated with CCs and other environmental effects. A toxicological approach could be useful.

The main recommendation is to further explore the relevance of the AOP framework in the context of CC. This requires identifying the current AOPs or key events in AOPwiki that may be relevant for CC effects, for example, inflammatory cytokines, oxidative stress, and skin sensitization (see text footnote 2ssssssw). Such AOPs may indicate possible interactions between CC and other stressors. For some CC factors, such as heat, it may be useful to develop new AOPs that can also be used to identify possible interactions.

Another related proposal would be to systematically look for interactions between different environmental factors and CC effects. This would support the identification of vulnerable individuals, problematic co-exposures, or possible antagonistic effects. For example, it would be interesting to determine the interactions between traffic- and industry-related air pollution and infectious diseases elicited by CC; indeed, the immune and inflammatory effects elicited by air pollution could interfere with the normal response to infections. Another example is the interaction between increased ozone and air pollution and lung diseases.

A specific focus on the effect of CC on children–particularly those sensitive to environmental stressors–is also recommended. The exposome concept highlights life-course effects, with childhood

2 https://aopwiki.org/

being a particularly vulnerable stage of development, in particular for neurocognitive functions. The combination of different stressors associated with CC (e.g., heat waves, extreme weather events, wildfires, and anxiety) may have a particularly detrimental impact on children.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

RB: Conceptualization, Formal analysis, Funding acquisition, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Inverting social innovation to transform health system responses to climate change adaptation and mitigation in the global south

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Systems thinking is aimed at understanding and solving complex problems that cut across sectors, an approach that requires accurate, timely, and multisectoral data. Citizen-driven big data can advance systems thinking, considering the widespread use of digital devices. Using digital platforms, data from these devices can transform health systems to predict and prevent global health crises and respond rapidly to emerging crises by providing citizens with real-time support. For example, citizens can obtain real-time support to help with public health risks via a digital app, which can predict evolving risks. These big data can be aggregated and visualized on digital dashboards, which can provide decision-makers with advanced data analytics to facilitate jurisdiction-level rapid responses to evolving climate change impacts (e.g., direct public health crisis communication). In the context of climate change, digital platforms can strengthen rapid responses by integrating information across systems (e.g., food, health, and social services) via citizen big data. More importantly, these big data can be used for rapid decision-making,a paradigm-changing approach that can invert social innovation, which we define as co-conceptualizing societal solutions with vulnerable communities to improve economic development with a focus on community wellbeing. However, to foster equitable and inclusive digital partnerships that invert social innovation, it is critical to avoid top-down approaches that sometimes result when researchers in the Global North and South collaborate. Equitable Global South–North partnerships can be built by combining digital citizen science and community-based participatory research to ethically leverage citizen-driven big data for rapid responses across international jurisdictions.

KEYWORDS
big data, citizen science, climate change, digital health, digital transformations, global health, global south, health systems

Introduction

Globally, the frequency and severity of climate change-related weather events, including heat waves, cyclones, and droughts, are exacerbating existing health and social inequities (1). These inequities are particularly apparent among vulnerable and disadvantaged groups in the Global South (1–12), especially in terms of living standards and human health (13–15).

Irrespective of the geographic region, the increasing burden on existing infrastructure, lack of resources, and financial constraints continue to prevent vulnerable populations from effectively managing the varied health risks of climate change (16–19). While there is an immense global effort to address climate change, the most negatively impacted communities are often not well represented in these critical conversations. In particular, Indigenous and racialized communities living in the most severely impacted areas are not always included in decision-making regarding mitigation and adaptation efforts (20–25). Moreover, some of the most vulnerable populations are living in densely populated regions of the Global South, with limited resources for climate change adaptation (5, 26–28)—a result of continuing historical injustices driven by centuries of colonization (28, 29).

The impacts of climate change on human health are complex, as they are linked to systems both within and outside of healthcare. For instance, the Intergovernmental Panel on Climate Change (IPCC) reports that the Global South is at a high risk of losing agricultural productivity (30–32) due to climate change (26, 33). Agricultural productivity is linked with various human health outcomes (i.e., the risk of communicable and non-communicable diseases) as well as living conditions (34). Climate change events, in general, have both direct and indirect impacts on health. These impacts include increased risk of heat stroke and cardiovascular stress during heatwaves (35), malnutrition from increasing food insecurity (36), and vector-borne infectious diseases due to frequent flooding (37). Climate change is also influencing mental health outcomes, with issues ranging from ecoanxiety and post-traumatic stress disorder to depression and suicidal ideation (38).

Globally, while health emergencies due to climate change have increased across all populations (27–29, 39), evidence clearly shows a disproportionate impact of climate change on vulnerable populations such as rural communities that rely on agriculture for livelihood (2, 3, 5, 40). However, according to the IPCC, a major gap in developing solutions is the lack of representation from vulnerable communities in the Global South (26). If the goals of the IPCC and United Nations Sustainable Development Goals are to be achieved, consistent and equitable engagement with communities experiencing the greatest vulnerability is critical (41–43).

Inverting social innovation

Equitable engagement requires consistent community consultation to amplify the voices of disadvantaged citizens. To enable equitable engagement, communication between community members and intersectoral stakeholders is necessary for a comprehensive climate change response—a complicated process requiring extensive coordination among groups (44–46). Each stakeholder group also requires access to accurate data and evidence, which are essential for making informed and timely decisions for complex intersectoral problems such as climate change. Inaccurate and invalid data from unreliable sources can result in disjoint and ineffective decision-making (44)—an issue that became apparent in the inadequate response to climate disasters across the world in the summer of 2023 (45, 46). Although there is no silver bullet for climate change adaptation and mitigation, there is an imminent need for a methodology that would amplify citizen voices and enable effective decision-making across sectors. Such a solution potentially lies in ethically obtaining citizen-driven big data via their own ubiquitous digital devices (47).

Citizen-driven big data refers to data that are high in volume, velocity, variety, and veracity (48, 49). Ubiquitous digital devices, such as smartphones, generate big data through the use of embedded sensors (i.e., global positioning system and accelerometers) and digital platforms, which can play an important role in time-sensitive health crises including climate change. The use of digital technology can be considered a social innovation. The Organization for Economic Co-operation and Development defines social innovation as the design and implementation of new solutions to improve the wellbeing of individuals and communities, with a focus on economic development (50). Citizen-driven big data can transform responses to climate change risks across jurisdictions through the use of digital platforms. In particular, these platforms can amplify citizen voices for two key climate change adaptation and mitigation solutions: (1) Provide citizens with near real-time support and (2) Ethically relay citizen big data to decision-makers for rapid responses (51). Most importantly, digital platforms powered by citizen big data are not limited by jurisdictional boundaries, i.e., they can transform responses to climate change risks across jurisdictions—a potential paradigm-changing approach to social innovation. However, with historical injustices limiting current resource access for climate change adaptation and mitigation strategies in the Global South (28, 29), it is time to *invert* our approach to social innovation.

Thus, we define inverting social innovation as co-conceptualizing societal solutions with disadvantaged communities to improve economic development, with a focus on community wellbeing. For a community solution to be categorized as inverting social innovation, it should address a critical societal problem by satisfying three key criteria: (1) transform weaknesses into strengths, (2) prioritize citizen needs over corporate profits, and (3) provide a pathway for rapid scale-up across jurisdictions. Inverting social innovation does not minimize the importance of economic development but aims to amplify the voices of citizens to address existential public health and social crises such as climate change.

Systems thinking

If there ever was an existential crisis that needed systems thinking to address its complexity, it is climate change (52, 53). Systems thinking is an approach to understanding and, ideally, solving complex problems that cut across disciplines and sectors. This holistic lens can potentially provide a pathway to develop and implement climate change adaptation and mitigation strategies which take into account the complexity of changing individual and contextual (i.e., social, ecological, economic, and political) risk factors. More importantly, these strategies may address determinants and risks within systems (e.g., food security—food supply within food systems) and across systems (e.g., food security and nutritional status across food and health systems) (54, 55). A systems thinking approach is essential for understanding the interdependent factors contributing to climate change and critical to identifying nodes of intervention within and across systems.

A significant challenge in monitoring, managing, and mitigating climate change impacts is the coordination of decision-making across systems (i.e., food, health, and social services) (54). The interdisciplinary expertise and trans-sectoral approaches that are required for coordinated decision-making can be transformed by ethically utilizing citizen-generated big data. Citizens' lives do not exist in silos, so why do we think about solutions to societal problems in silos? Given that citizen-generated big data can cut across disciplines and sectors, systems thinking can be operationalized using digital citizen science (56). In the 21st century, human engagement with and through Internet-connected ubiquitous devices, such as smartphones, generates an enormous amount of big data (57). These big data can be used to understand and address complex, trans-sectoral problems. The use of big data can have significant positive implications for prediction, prevention (i.e., mitigation), and adaptation to climate change risks.

Digital platforms that are powered by citizen-driven big data offer a range of potential benefits, which include: (1) direct citizen-decision-maker communication to help mitigate and manage existing and emerging crises and (2) real-time support for citizens to improve their own decision-making during climate crisis (43). For example, citizens can obtain support in real time to help manage public health risks via an app that can predict evolving risks by taking into account both citizen as well as environmental big data. These big data can be aggregated and visualized on digital dashboards to facilitate jurisdiction-level rapid responses to evolving climate change impacts (e.g., direct public health crisis communication). The use of digital citizen science with systems thinking is a paradigm-changing approach that will invert social innovation, as it prioritizes community needs and, importantly, enables advancements in digital health for equity (43).

However, developing and implementing system-wide policies are extremely challenging without the timely collection, analysis, and visualization of data. It is evident that disparate information from multiple sectors can result in disjointed decision-making (26). To overcome this challenge in decision-making, it is imperative to adapt, implement, and evaluate existing digital platforms across jurisdictions, i.e., generate empirical evidence of their effectiveness. The operationalization (adaptation, piloting, implementation, and evaluation) of digital platforms for decision-making intersects multiple disciplines, including but not limited to computer science, data science, digital epidemiology, environmental sciences, global public health, implementation science, and program evaluation. This operationalization also transcends sectors, and can vary across jurisdictions, while maintaining standardized methods for rapid replication. However, to ensure the actual application of interdisciplinary and trans-sectoral approaches through systems thinking, it is critical to utilize previously tested and implemented frameworks that integrate citizen science with community-based participatory research via digital transformations (56).

One such framework is the Smart Framework, which has been consistently used to implement a range of innovative interventions, such as climate change adaptation (46, 58), co-creation of digital solutions for equity and justice (58), ethical surveillance promoting data sovereignty (59), and rapid jurisdictional decision-making (60). The application of the Smart Framework is driven by the integration of citizen science and community-based participatory research in addressing societal crises such as climate change. To enable this integration, the framework proposes repurposing citizen-owned internet-connected ubiquitous tools to sense, share, and link big data that power digital health platforms. In essence, the framework proposes that digital health platforms powered by citizen-driven big data can facilitate equity by amplifying disadvantaged citizen voices to inform policies—a key gap identified by the IPCC in current climate change solutions (26, 41–43). However, from a Global South perspective, as proposed by the Bridge Framework, systems thinking needs to go beyond sourcing big data from citizens to identifying processes for decolonizing citizen science to reverse historical injustices of colonization (61). Decolonizing citizen science is critical to ethically partnering with disadvantaged communities, where big data should aim to capture traditional local knowledge that is crucial for developing local solutions for global problems such as climate change. Hence, we propose the integration of concepts from both Smart and Bridge Frameworks to operationalize systems thinking via digital health platforms to address climate change impacts.

Discussion

The foundation of citizen big data-driven digital health platforms for decision-making is co-creation (62). This involves the intersection of digital citizen science (i.e., direct engagement with all participants) and community-based participatory research action (i.e., direct engagement with jurisdictional decision-makers and leaders). The use of citizen-owned devices provides an avenue for big data collection, but perhaps more importantly, an opportunity to amplify citizen voices and empower those who experience marginalization to inform jurisdictional policies—a key component of co-creation (63). In addition to direct engagement with citizens, partnering with jurisdiction-specific Citizen Scientist Advisory Councils can facilitate concrete governance structures (47).

An efficient approach in developing digital health platforms for decision-making is to scale-up (43), replicate, and repurpose existing digital health infrastructure (64–67). Repurposing existing digital infrastructure aids rapid responses irrespective of the location of implementation—a capability that is critical for climate change adaptation and mitigation. Following this replicability-focused approach, emerging cutting-edge evidence indicates that the first step in developing and implementing digital health platforms for decision-making is to adapt existing cloud-based and *decentralized* digital infrastructure (51). An important aspect of this infrastructure is progressive web applications that can be built with web technologies, installed, and run on all digital devices or web browsers without the need to launch on Google and Apple stores (31). In essence, this decentralized approach can minimize dependency on big technology companies in responding to climate change (32, 51).

However, digital health platforms for climate change adaptation and mitigation must also enable real-time communication with citizens, particularly given the urgency of climate change events. This is a key component of enabling self-determination and sovereignty in the Global South (33). Such digital platforms can provide real-time support to households to manage key health risks within their jurisdiction by using advanced algorithms that will adapt to each household's needs. All data from individual households can be encrypted, aggregated, and anonymized before being relayed to a digital decision-making dashboard to be housed with the key decision-makers in each jurisdiction. Decision-makers can use digital health dashboards to sustain real-time support for citizens and use big data for rapid responses (33, 51). For instance, decision-makers can send jurisdiction-specific disaster management alerts to mitigate and manage health risks, irrespective of the disaster (i.e., earthquakes, droughts, flooding, and forest fires) (51). The most advanced versions of these digital health dashboards can also support anonymous bi-directional engagement with citizens (51). In essence, these digital platforms can provide value perspective (i.e., real-time support) to citizens while amplifying citizen voices and contributing big data for a larger cause—jurisdictional responses for climate change adaptation and mitigation.

This value perspective is critical for the success of the infrastructure scale-up because it motivates citizens to participate in digital health platforms. Most importantly, the same digital health infrastructure could be modified to address jurisdiction-specific climate change issues ranging from infectious diseases (47) and non-communicable diseases (56) to systemic issues such as food security (68). This approach can transform the integration of health systems with other critical systems (i.e., environment, food, social services, and disaster management) to enable rapid responses for climate change adaptation and mitigation.

To replicate and scale-up digital health infrastructure for climate change adaptation and mitigation, equitable partnerships between decision-makers, researchers, and key community stakeholders in the Global South and North are paramount. To enable the meaningful inclusion of all research partners in the core decision-making processes of digital health infrastructure scale-ups, it is crucial to make a concerted effort to avoid top-down approaches that sometimes result when researchers in the Global North and South collaborate, i.e., a core systemic barrier to equitable partnerships (69, 70). Integrating digital citizen science with community-based participatory research (56, 61) can enable an equity-focused perspective to ensure meaningful partnership, participation, and contribution from all countries involved. The operationalization of this approach should start from the co-conceptualization stage itself, where representatives from each country are involved in establishing key risks, core objectives, data collection, and knowledge dissemination strategies. Since countries in the Global South continue to experience the most severe impacts of climate change, they should take the lead in informing digital health infrastructure adaptation and implementation.

The sustainability of digital health infrastructure will depend on training and development opportunities in each jurisdiction to essentially create a path for long-term capacity building. In implementing cutting-edge digital health infrastructure in the Global South, equitable technology transfer should be matched with the development of local technological skills. Ultimately, to implement digital health platforms, meaningful citizen involvement is key, particularly among vulnerable or marginalized communities experiencing the brunt of adverse climate change impacts. Thus, jurisdiction-specific Citizen Scientist Advisory Councils (68) can serve as co-creation and implementation partners, expanding the applicability of research findings and technology across society. Citizens interested in obtaining specific skills, such as interpretation of data, can be provided with training opportunities as part of efforts to build capacity. Given the disproportionate impacts of climate change on certain subgroups within communities (i.e., women and low-income households), successful implementation of digital health platforms also relies on their contribution to Citizen Scientist Advisory Councils.

Equitable Global South–North partnerships are the first step in ethically obtaining big data directly from disadvantaged citizens in the Global South (71, 72). These Equitable Global South–North partnerships can also lay the foundations for the data sovereignty of disadvantaged citizens in the Global South. As any digital ecosystem comes with risks of data exploitation, equitable partnerships can ensure that citizen data are secured within their jurisdictions by aligning with jurisdictional data regulations (51). However, to reverse historical injustices that the Global South continues to perpetuate (28, 29), we need to go above and beyond jurisdictional data legislation. One small step would be to use secure cloud computing to facilitate the data sovereignty of citizens, where citizens own their data (62).

Ultimately, if we are to transform health systems for climate change adaptation and mitigation in the global south, the three criteria for inverting social innovation provide a preliminary framework: (1) Transforming weakness into strengths: The 2022 IPCC report indicated a dearth of representation from disadvantaged communities in the development of climate change solutions. This gap can be addressed by decolonizing our approaches where diverse citizen voices are amplified via big data—an approach that has immense potential due to increasing ownership of not just ubiquitous devices such as smartphones, but also affordable access to data plans in the Global South (73–76). However, we cannot place all Global South countries in one box, as there are wide variations of access to mobile devices and data both within and across countries (77–79). Nevertheless, ubiquitous tools have transformative potential for health systems as well as people in the global south – if they are re-purposed ethically to utilize citizen-driven big data for climate change adaptation and mitigation; (2) Prioritizing citizen needs over corporate profits: Digital health platforms not only provide citizens with real-time support, but also relay aggregated and anonymized big data to jurisdiction-specific digital dashboards to enable decision-making, i.e., the needs of citizens and decision-makers of specific jurisdictions are prioritized; and (3) Providing a pathway for rapid scale-up across jurisdictions: The decentralized structure of the digital platforms for decision-making allows rapid scale-ups to adapt and mitigate climate change impacts specific to different jurisdictions, i.e., local solutions for global problems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TRK: Writing – original draft, Writing – review & editing, Conceptualization, Funding acquisition, Methodology. JB: Writing – original draft, Writing – review & editing, Conceptualization, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The potential of virtual healthcare technologies to reduce healthcare services' carbon footprint

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The COVID-19 pandemic demonstrated the potential to reduce our carbon footprint especially by reducing travel. We aim to describe healthcare and health education services' contribution to the global climate emergency and identify the need for increased use of virtual health service delivery and undergraduate/postgraduate education to help reduce the impact of health service and health education delivery on the environment. Health care services, as one of the largest contributors to carbon emissions, must take steps to rapidly reduce their carbon footprint. Health services have unfortunately paid little attention to this issue until recently. Virtual healthcare and education have a valuable role in transition to a net carbon-zero outcome. Given the increasing use of and satisfaction with virtual health services such as telehealth, and the increase in virtual education opportunities, it is important that a concerted effort is undertaken to increase their use across health services and education in the future.

KEYWORDS

telehealth, planetary health, virtual healthcare, carbon emissions, digital healthcare, virtual health education, climate change

Introduction

The potential of virtual healthcare technologies to reduce healthcare services' carbon footprint

Healthcare services have become one of the largest contributors to greenhouse gas emissions (GHG) globally accounting for 4.4% of net GHG emissions (1, 2) as modern medical technology has become carbon emission intensive (3). Unfortunately, the healthcare sector continues to contribute significantly to GHGs (4). In fact, the healthcare sector has a significant and growing carbon footprint through energy consumption, transport, and product manufacture, use, and disposal (2). Unfortunately, healthcare services have only recently taken notice of this issue (2), and thus lag other sectors in taking action to reduce their climate impact (5). Tertiary education institutions, where most health professional education is delivered, are also high contributorus to GHGs mostly through travel, electricity and water consumption, and paper usage (6). Given the need for most health students to travel to attend mandatory clinical placements, which for some students amounts to large distances, is a growing concern.

Given the serious impacts of climate change on human and animal health and on the environment, it is timely to reflect on the carbon footprint of health and health education services and take action to reduce this footprint. It is paradoxical that the health sector, responsible for improving health outcomes, also directly contributes to poor health outcomes through excessive carbon emissions. The COVID-19 pandemic dramatically changed the way healthcare services and health education are delivered including an increased use of virtual technologies, especially telehealth, in place of face-to-face appointments and online teaching in place of face-to-face teaching. Telehealth services, which include telephone and video consultations as well as digital monitoring devices, also have benefits for the consumer. Travel costs and time away from home/work/family are reduced, access to services, especially specialist services for people living in rural and remote areas, is enhanced, chronic conditions are better managed as telehealth makes regular follow-up possible, wait times to see specialists are reduced, readmissions are decreased, and exposure to other patients and the general public in waiting rooms and during travel is reduced (7, 8). In addition, given that evidence suggests virtual student education has similar outcomes to real-life clinical placements (9), efforts need to be made to increase these opportunities for students.

Virtual health as a strategy to reduce the health service carbon footprint

Among the contributors to health's carbon footprint is the use of road and air travel for patients to attend face-to-face healthcare consultations, and travel by staff to consult with patients in rural and remote locations including their home, and to attend meetings (4). Experiences arising from the COVID-19 pandemic provide important data that demonstrates how health services' contribution to GHGs can be reduced. During the pandemic, the use of virtual health technologies such as telehealth (both video and telephone consultations) increased dramatically (10) and subsequent research has shown that virtual healthcare not only offers a satisfactory alternative to face-to-face consultations but also reduces the need for patients (and providers) to travel (11). Tsagkaris et al. (3) claim important learnings from the COVID-19 pandemic include that virtual healthcare technologies such as telehealth offer effective alternatives to face-to-face healthcare visits, reducing the need for patients to travel to attend health consultations and reducing environmental costs (4). Reducing unnecessary patient travel has been identified as an effective way of reducing the carbon footprint of health services (12). Telehealth services such as video and telephone consultaions and in-home digital monitoring devices offer a means of achieving this outcome.

Telehealth (also called telemedicine) is a recent development. It describes various forms of remote consultation that can encompass a range of digital tools including both video and telephone consultations and digital monitroring devices (13, 14). A recent review highlighted issues around accessibility and establishing a therapeutic relationship as among the major concerns in the use of video abd telephone telehealth platforms (14). There is evidence to suggest that video supported telehealth is preferred over telephone consultations and that telehealth is rated as more effective than telephone consultations by patients (15). Telephone consultations however generally require a lower level of digital literacy and may represent enhanced accessibility over other methods for remote consultations (14). Overall, telehealth has been viewed satisfactorily by patients (16, 17) with benefits including less travel, less time away from home and work, and lower costs (18).

Other virtual healthcare innovations such as digital devices (including wearable and implantable devices, remote imaging, and mobile apps), allow patients to be assessed and monitored effectively at home (1, 4, 19, 20). These alternative means of health assessment and monitoring, and healthcare delivery offer potential to reduce the carbon footprint of healthcare services, by reducing the need for patients and staff to burn fossil fuels while traveling to attend healthcare consultations and home or clinic visits (18). There is also a likely reduction in the scope of emissions, associated with disposables and consumables (12), with remote consultations. The environmental benefits of the reduction of travel were demonstrated during the COVID-19 pandemic when an 8.8% reduction in global emissions reported in the first half of 2020 compared to the same period of 2019 (21). While there have been some concerns raised about the use of virtual health technologies acceptance, use of virtual health is increasing (18, 22).

Potential for virtual health undergraduate and postgraduate student clinical placements to help reduce the carbon footprint

There is an urgent need to develop more sustainable health education practices to help reduce climate change. Unfortunately, it appears that while health educators have the knowledge to do this, they lack the pedagogical expertise to teach this information (10). To address this issue, a recent Australian study identified the need to embed sustainable health education, policy and practice using "…an evidence based, interdisciplinary whole health and tertiary education approach" (p. 325) (23). Most health professional training programs require students to undergo workplace training under the supervision of an experienced educator/clinician. Nursing regulatory bodies in the United Kingdom and United States have already supported the replacement of some face-to-face clinical placements with virtual simulation (24). Virtual simulation activities have the potential to reduce the need for travel to attend clinical placements hence reducing GHG emissions and reducing student costs.

Evaluations of virtual simulation placements in nursing are positive with a recent study finding that the virtual clinical replacement experience was statistically significant reporting greater confidence in areas such as patient safety, communication, and leadership, as well as greater perceived support in the workplace (9). The use of virtual simulation with medical students has also been positive with students reporting being better prepared for the clinical environment (25). Virtual technologies offer an adjunct or even an alternative to clinical placements that can help reduce the health services' carbon footprint.

Evidence that reduced travel leads to reduced GHG emissions

A Spanish study by Morcillo Serra et al. (26) found that 640,000 digital consultations and 3,060,000 medical reports downloaded remotely by patients during the COVID-19 pandemic in 2020 avoided an estimated 6,700 net tons of CO^2 emissions. That study demonstrates the potential reduction in GHG that can be achieved through the increased use of virtual health. Numerous studies have been recently conducted that demonstrate similar reductions if virtual health was used as an alternative to traditional consultations (4, 27). While there is the potential for increased GHG emissions associated with use of electricity used to power increased digitalisation of healthcare services, often overlooked in many studies conducted to date, these increases were found to be far less than those associated with patient and staff travel (4, 27). In one study that did include assessment of energy used to run equipment for telehealth, it was estimated that telerehabilitation services resulted in carbon cost savings when the patient travels over 7.2 kms to attend the appointment (28). It is important to remember that the different virtual technologies use differing amounts of GHGs with video enhanced telehealth more GHG emission intensive than telephone calls (4). The review by Purohit et al. (4) reveals the importance of considering the medical specialty, geography, and time. It seems that the higher the level of specialization corresponds with a greater reduction in travel, since specialized centres serviced a wider geographic region. For example, studies of telephone consultations in place of face-to-face visits have been evaluated. A study of post-renal transplant services telephone follow-up appointments for 30 patients resulted in a saving of 39.3 km travel equating to a saving of 8.00 kg CO_2 per consultation (29), and a study of pre-surgical telephone consultations in Texas, where large distances were traveled to the one specialist service, resulted in carbon footprint reductions of 271 kg CO_2 per consultation (30). Similarly, evaluations of video conference CO_2 savings have also been positive. For example, the use of videoconferencing for telerehabilitation in Sweden which included the energy consumption of the equipment as well as travel savings demonstrated that 238 appointments resulted in a saving of 82,310 km giving a range of 87.5–175 kg CO_2 per consultation (28).

Need for urgent action

A recent editorial (31), identified the need for urgent action and proposed we are facing a global health emergency. Health services must not only deliver healthcare to those made ill from the climate crisis, but also radically reduce their own emissions (2). Health professionals and educators must take an urgent role in developing and utilising strategies that help reduce the health services' and health education carbon footprint. In Australia, where health travel is extensive due to the size of the country, it is even more urgent to tackle this wicked problem. Outside of emergency responses, telehealth has shown to have similar outcomes to standard consultations for many health conditions including diabetes and cardiac conditions (27). Greater implementation of virtual healthcare and education technologies offers an opportunity to reduce the need for travel and in turn, reduce the healthcare carbon footprint. Efforts are needed to ensure research approaches, education and policy are developed to facilitate greater use and evaluation of virtual healthcare services. Similarly, educators need to look for opportunities to reduce the need for travel, especially travel over large distances, for students to attend clinical placements or fieldwork requirements. The potential for carbon emission reductions in this area is huge.

Conclusion

Health services, as every sector of society, have a responsibility to take action to reduce the impacts of humans on the environment. Virtual healthcare and education services have a valuable role in transition to net carbon-zero healthcare/education services for the future. As the current evidence suggest a strong relationship between carbon footprint reductions and average distance travelled, countries with larger distances to travel for face-to-face consukltations may benefit more by enhancing their use of telehealth services for patient consuktations where possible. Given the increasing use of and satisfaction with virtual health services such as telehealth, it is important that there is a concerted effort to increase their use across health services. It is also imperative that health education adopts ways to improve student/educator awareness of the need to reduce the health carbon footprint and adopts virtual health education practices that have the potential to further reduce the current health education carbon footprint. Given the need to reduce the GHGs emitted by health services and education services, health professionals and educators have a pivotal role in building healthier, more equitable and sustainable health services and education by adopting practices that have a lesser impact on the environment. Greater efforts are needed to ensure research approaches, education, and policy are developed to support the increased use of virtual healthcare services and undergraduate and postgraduate student clinical placements, and to ensure ongoing evaluation of these services as they are integrated into mainstream healthcare and tertiary education.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

KU: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. JW: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. DJ: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Healthcare-related carbon footprinting—lower impact of a coronary stenting compared to a coronary surgery pathway

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Healthcare is a major generator of greenhouse gases, so consideration of this contribution to climate change needs to be quantified in ways that can inform models of care. Given the availability of activity-based financial data, environmentally-extended input–output (EEIO) analysis can be employed to calculate systemic carbon footprints for healthcare activities, allowing comparison of different patient care pathways. We thus quantified and compared the carbon footprint of two common care pathways for patients with stable coronary artery disease, with similar clinical outcomes: coronary stenting and coronary artery bypass surgery (CABG). Healthcare cost data for these two pathways were disaggregated and the carbon footprint associated with this expenditure was calculated by connecting the flow of money within the economy to the greenhouse gases emitted to support the full range of associated activities. The systemic carbon footprint associated with an average stable patient CABG pathway, at a large tertiary referral hospital in Sydney, Australia in 2021–22, was 11.5 tonnes CO_2-e, 4.9 times greater than the 2.4 tonnes CO_2-e footprint of an average comparable stenting pathway. These data suggest that a stenting pathway for stable coronary disease should be preferred on environmental grounds and introduces EEIO analysis as a practical tool to assist in health-care related carbon footprinting.

KEYWORDS

footprint, carbon emissions, greenhouse gases, patient care pathway, sustainability, stenting, bypass surgery, input–output analysis

1 Introduction

Addressing the contribution of healthcare to climate change is a major current public health challenge. Global studies confirm that healthcare, a service industry with extensive supply chains, has a large carbon footprint and consequent climate change impact (1–3). This same high level of impact has also been demonstrated at the national level for many countries, including Australia (4). As a result, there is growing pressure on the healthcare sector to deliver reduction of emissions of greenhouse gases (GHG) such as carbon dioxide, methane, nitrous oxide, and a range of medical and industrial gases (5). In response to this pressure, work is now starting on factoring in GHG emissions in health-care decision making (6). For example, modelled on a UK example (7), the health department of New South Wales (Australia) is focused on improvements in energy and emissions efficiency at the facility level, addressing the state's net zero emissions target (8). Similarly, as the Australian Government National Health and Climate Strategy (9) recognises, an understanding of the emissions generated across the full healthcare system to support a particular patient care pathway—its "carbon footprint"—could contribute to public health decision making by informing models of care optimised for both health and environmental benefits. While data alone are not sufficient to support systemic change, or changes at the level of medical practitioner decisions, readily accessible data on the emissions profiles of different procedures are a necessary condition for both. Particularly when combined with other policy and educational tools, it can support health system and clinical decision changes, to significantly lower emissions.

Global and national studies of the healthcare sector's carbon footprint are usually derived from a modelling approach known as environmentally-extended input–output analysis (EEIO) (1–4). EEIO analysis quantifies the environmental impact associated with expenditure on goods and services using economic input–output tables. These tables contain information on the flow of money through the economy and the environmental impacts associated with the economic activity represented by that flow. By covering the whole economy, they are effectively "boundaryless." As a result, EEIO can provide a comprehensive systemic footprint of any sector or activity accounted for in the input–output tables, including the healthcare sector. Recently there has been a study that extends the resolution of EEIO analysis to the level of an Australian state-based health sector organisation, using expenditure data sourced directly from internal accounts (10). This increase in resolution assists in bringing the carbon footprint into clinical decision-making and assists health managers to achieve sustainable value in healthcare (10). However, it does not provide insights into the carbon footprint of a particular patient care pathway.

There is a rapidly expanding literature looking to understand contributing activities to heath care carbon footprints. For the most part, analysis at this level employs methods that are variations on a different modelling approach to quantifying emissions, called unit process Life Cycle Assessment (LCA) (9, 11). LCA uses physical data on the relevant process collected from metering, observations, manufacturer's specifications, and from detailed proprietary LCA databases, to assess the associated environmental impacts. By using physical data, LCA provides specific analysis on how emissions are generated, which can inform decision making in areas such as alternative product selection and optimising engineering specifications. This approach is being widely used in Australia, and has been used, for example, to estimate the carbon emissions of pathology testing (12), diagnostic imaging (6), and treatment of septic shock in an intensive care unit (13).

Because EEIO provides a sectoral analysis it is often characterised as a 'top down' carbon footprinting approach (9), contrasted with the 'bottom up' analysis of specific healthcare activities provided by LCA. This is usually taken to mean that EEIO is appropriate only for broad, jurisdictional and enterprise analysis and that LCA is the appropriate tool for detailed, activity-based analysis. However, a recent German study used EEIO derived emission factors to estimate the carbon footprints of hospital care pathways for an annual cohort of patients with acute decompensated heart failure at a German hospital (14). Building on this example, we propose that, given activity-based financial data, EEIO can also be employed to calculate systemic carbon footprints for quite specific healthcare activities, like surgical procedures. Moreover, we suggest that the use of EEIO at the activity level has certain advantages. Cumulatively these systemic footprints promise to account for the entire carbon footprint arrived at through national and enterprise carbon footprints. Unlike more tightly scoped LCA studies, these systemic footprints tend to be very much larger, incorporating the entire patient care pathway from admission to discharge, rather than a particular clinical procedure like surgery, or anaesthesia. These systemic footprints are also boundaryless, covering the entire extended supply chain that supports the healthcare activity in question. Irwin et al. estimate the extended supply chain (including postal, business and accounting services) accounts for 47% of Western Australian Health's organisation's carbon footprint, similarly Tennison et al. estimate the extended supply chain accounts for 62% of England's National Health Service (NHS) footprint (3, 10). Further, as EEIO calculations are boundaryless and calculated using shared monetary units, they allow comparison of very different activities, whereas to arrive at comparative results, LCA studies need to be individually scoped to compare specific activities that share a functional unit. Finally, unlike LCA, which depends on sourcing physical data through resource intensive measurement, EEIO draws on readily available financial data and as such, can be more easily calculated. Given the urgency of measuring emissions across scales, this is an advantage, especially in cases where the emissions of different procedures are being compared. Our argument is not that EEIO should replace LCA, it is rather that EEIO analysis can usefully supplement LCA.

To exemplify how EEIO can be applied to calculate the systemic footprint of healthcare activities, and how these can be compared, this paper aims to quantify and compare the systemic carbon footprint of the patient care pathways associated with two common procedures with near-equivalent clinical outcomes. Our choice of example is informed by the fact that cardiovascular diseases in general, and coronary artery disease in particular, are the most common non-communicable diseases worldwide (11). However, as research into the climate impacts of cardiovascular healthcare is only just emerging (11), there is an absence of climate considerations in clinical guidance on the management of coronary artery disease, which do, however, indicate very important economic considerations. For example, the Australian Clinical Guidelines for the Management of Acute Coronary Syndromes do not mention climate considerations but do promote "cost-efficient improvement in patient outcomes as a result of new innovations in care" (15).

Many studies have compared clinical outcomes (survival, complications, quality of life) and economic costs of percutaneous transluminal coronary angioplasty (now nearly exclusively stenting); and coronary artery bypass graft surgery (CABG), in a wide range of disease states. In general, stenting is favoured in the setting of acute coronary syndromes and in stable single vessel disease, whereas surgery is more commonly favoured in diabetic patients and/or those with triple vessel disease (16–18). CABG and stenting generally share comparable clinical pathways prior to admission (diagnosis, referral and hospitalisation) and following discharge (ongoing monitoring) (19). They are also largely similar regarding survival outcomes and quality-of life measures (20). Thus, to ensure we chose an example with clinical equipoise, we compare the carbon footprints of stenting and CABG in stable, non-diabetic patients with two-vessel coronary disease (19). The argument we make in this paper is that the calculation of healthcare activity systemic carbon footprints can and should assist in introducing climate change considerations into decisions on the choice of patient care pathways.

2 Methods

2.1 Data

In using EEIO for their carbon footprint assessment of the National Health Service (NHS) in England, Tennison et al. note that a major limitation is that the "NHS's internal spending information does not capture breakdown by economic sector and so was not used; instead, total spending on health care tracked by HM Treasury was proportioned using the transaction matrix in the UK MRIO model."(3 p. 86–7). However, health care organisations in many jurisdictions globally now use activity based costing to help address economic efficiency and these data can be aligned to economic sectors (21). Australia uses activity-based funding in the healthcare sector whereby public hospitals get paid for the number and mix of patients they treat. To calculate the amount of the Australian Commonwealth Government's payments to local hospital networks on an activity basis, the Independent Health and Aged Care Pricing Authority is responsible for determining the annual national efficient price and national efficient cost. To inform the calculation of these, Australian public hospitals routinely collect and report cost data as part of annual National Hospital Cost Data Collection (NHCDC) rounds (22). During each round, hospitals identify and classify all relevant costs into predetermined categories according to the NHCDC data request specifications and the Australian Hospital Costing Standards (23). These costs are then aggregated to cost buckets as specified in the relevant pricing framework (23). This process accounts for the direct and indirect costs of a care pathway, including specific procedures, from admission to discharge. This care pathway is referred to as a patient encounter. It includes all expenditure by the health care provider spent on this episode of care, including an apportionment for the general operation of the hospital and wider health system, and the specialised equipment required, such as a heart-lung machine or angiogram device. These cost bucket data can be aligned to economic sectors, enabling EEIO analysis.

Having restricted our sample to patient encounters associated with a pair of clinically equivalent procedures, we further minimised the variables in this novel application of the EEIO methodology by sampling a single hospital for 1 year to maximise the consistency of accounting practices that allocate expenditure to cost buckets. Cost data for NHCDC for the financial year 2021–22 (Round 26) were obtained from the Sydney Local Health District (SLHD) for costs incurred by Royal Prince Alfred Hospital (RPAH), a tertiary and quaternary referral hospital, for the elective surgical treatment of two-vessel coronary stenoses, by either:

1 Coronary artery bypass using 1 left internal mammary artery grafts (LIMA) graft: procedure code 38500–00; and coronary artery bypass using 1 saphenous vein graft: procedure code 38497–00 ($n = 32$)
2 Percutaneous insertion of >=2 transluminal stents into multiple coronary arteries: procedure code 38306–02 ($n = 29$)

The SLHD had information by cost bucket by each procedure and by each patient, supplied for this analysis in the form of an average by cost bucket associated with each procedure. The cost data provided by SLHD were allocated to 16 different cost buckets for each procedure, according to the NHCDC Pricing Framework (23). Addressing the issue raised by Tennison et al. (3), the data were then disaggregated and allocated to sectors within Australia's economy, informed by the Australian Hospital Patient Costing Standards (23), which provide detail on what expenditure types are accounted for in each cost bucket. Where costs from the same cost bucket were allocated to more than one economic sector, the allocation was weighted based on the ratio of expenditure on those sectors by the Australian healthcare sector in the 2021–22 financial year, which provided the industry average. The types and definitions of cost buckets are summarised in Table 1.

These cost data required disaggregation to the 1,284 economic sectors provided in the single-region input–output table built using the Australian Industrial Ecology Laboratory (23). This disaggregation was executed by building a concordance matrix, allocating the total expenditure through the matrix, and excluding costs that are not included in final demand within the input–output table, which would otherwise result in double counting. These steps are detailed below.

2.2 Step 1—building a concordance matrix

A binary concordance matrix was built based on the details included in NSW Health's accounting framework. A concordance is a binary matrix which connects two different sets of information, in this case the sector structure used to report economy-wide transactions in the input–output table, and the cost bucket structure used to report the SLHD cost data. An extract of the concordance used for this study is included in Figure 1, where a value of 1 in a cell represents a connection between the data reported within the input–output table (in the rows) and the cost bucket data received from SLHD (in the columns).

Assumptions made in the creation of this concordance include:

- Any maintenance and repair costs are matched to the non-clinical cost bucket;
- The pathology, pharmacy, critical care and imaging cost buckets includes the cost of relevant staff;
- Higher value capital purchases such as medical equipment and furniture are matched to the cost bucket where they will be used, such as OR and SPS;
- Non-medical equipment and furniture are matched to the non-clinical cost bucket;
- Consumable items are matched to the Ward & ED supplies cost bucket if they are used for the clinical care of patients (e.g., bandages); and
- Consumable items are matched to the non-clinical cost bucket if they are not directly used in the clinical care of patients (e.g., cleaning supplies).

TABLE 1 Cost bucket definitions for data provided by SLHD and allocation of costs.

Cost bucket codes	Cost bucket description	% costs by cost bucket for CABG procedure	% costs by cost bucket for the stenting procedure
Allied	Allied Health: Average cost-includes clinical services which costs are recorded against the allied health cost centres.	2.12%	1.67%
Med	Medical: Average cost-includes the salaries and wages of medical officers including visiting medical officer (VMO) payments.	9.38%	4.83%
Nurse	Nursing: Average cost-includes the nursing salaries and wages of medical clinical service or ward cost centres.	7.04%	5.50%
Critical care	Critical care: Average cost-includes clinical services which costs are recorded against critical care cost centres as in adult intensive care unit (ICU), coronary care units, cardiothoracic ICU, high dependency units, neonatal & paediatric ICU, psychiatric ICU, special care nurseries.	20.97%	15.26%
Imag	Imaging: Average cost-includes services which costs are recorded against imaging cost centres and imaging costs recorded against an imaging account code.	1.87%	2.16%
OR	Operating Room/Theatre time (in minutes) is a combination of theatre duration and recovery duration.	20.89%	1.54%
Path	Pathology: Average cost-includes services which costs are recorded against pathology cost centres and pathology costs recorded against a pathology account code.	4.48%	3.13%
Pharm	Pharmacy: Average cost-includes services which costs are recorded against pharmacy cost centres and pharmacy costs recorded against a pharmacy account code.	0.66%	0.24%
Pros	Prosthetic: Average cost-includes services which costs are recorded against a prosthetic account code.	1.24%	9.30%
SPS	Specialist procedures suite: Average cost-includes all goods and services (excluding prosthesis), salaries and wages and VMO payments for SPS.	0.29%	32.92%
Ward & ED Supplies	Ward and emergency department (ED) supplies: Average cost-includes medical and surgical supplies and goods and services cost in clinical cost centres.	13.40%	2.69%
Non Clinical	Non-clinical: Average cost includes all costs associated with hotel (such as cleaning, linen and food), the salaries and wages of administrative and non-clinical staff.	5.94%	5.88%
On Cost	On cost: Average cost-includes superannuation and workers compensation costs.	4.91%	4.48%
Exclude	Includes costs which are not included in the pricing model and are excluded from the total cost in the portal such as Interest PPP, Depreciation and Actuarial Costs	3.54% + 1.26% Portal	2.13% + 1.27% Portal
Covid	COVID cost bucket includes the additional expense such as cleaning, security and PPE that has been due to the COVID-19 pandemic	1.47%	1.63%
PatTrans	Patient Transport cost bucket. Average cost-includes the costs associated with patient transportation.	0.51%	5.36%
Total %		100%	100%

2.3 Step 2—allocating the total expenditure

Where expenditure in one cost bucket was connected to more than one input–output sector, for example the non-clinical cost bucket, the percentage used to allocate the total expenditure in that cost bucket to the relevant input–output sectors was determined using the Australian healthcare industry average expenditure across each of the component sectors. The data for this was sourced from the intermediate demand matrix within the 2021–2022 input–output table. This meant, for example, that 1.6% of the costs recorded under the non-clinical cost bucket were allocated to expenditure against the electricity generation sectors. At this point, all costs included in each cost bucket were allocated to one or more sectors within the input–output table.

2.4 Step 3—excluding costs not covered in final demand

A final adjustment was made to the expenditure values allocated to each of the economic sectors within the input–output table to exclude any expenditure that did not constitute final demand within them. This includes expenditure on salaries and wages, which is captured in the value-added matrix in the input–output table. The exclusion of any expenditure that did not constitute final demand extends also to capital expenditure, present in the cost bucket data as depreciation, an accounting mechanism for allocating capital expenditure that has already been incurred. This expenditure was assigned by SLHD to the 'Excluded' bucket. This exclusion resulted in an underestimate of the systemic footprint, since it did not include emissions associated with expenditure on capital items during the 2021–22 financial year. This is recognised as a limitation of our method, which might be best described as an operating systemic carbon footprint. Both these adjustments are routinely made in studies of this sort (14).

2.5 Analysis—environmentally-extended input–output analysis

Environmentally-extended input–output (EEIO) analysis, a well-established methodology for calculating carbon footprints (4), was used to calculate the carbon footprint for these two cardiac procedures. This methodology, introduced by Wassily Leontief (24), relies on matrix calculations to connect the flow of money within a given economy, represented in an input–output table, to the greenhouse gases emitted by activities in that economy. This approach has been widely used to understand carbon footprints across the global economy in recent decades but is still novel as a tool for measuring patient care pathways (1, 4). Key to these calculations is Equation 1, which connects the economic transactions captured in the input–output table to the environmental impact generated by those economic transactions.

$$\text{footprint} = \mathbf{qLy} \tag{1}$$

Here, $\mathbf{q}$ represents the direct intensities vector, providing information on the greenhouse gases emitted for every dollar of total output for each sector in the input–output table. The $\mathbf{L}$ matrix, also known as the Leontief inverse, provides information on the economic interdependencies within and between all sectors within the economy by quantifying the value of total input required from each sector to produce one dollar worth of output for a given sector. It is derived using Equation 2, where $\mathbf{I}$ represents the identity matrix (the matrix equivalent of the number 1) and $\mathbf{A}$ represents the direct requirements matrix. The direct requirements matrix $\mathbf{A}$ is calculated from the data within the input–output table by dividing each transaction in the intermediate demand matrix, which provides information on the value of transactions between sectors within the economy, by the total output for each sector.

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{2}$$

Finally, the $\mathbf{y}$ vector in Equation 1 provides information on the expenditure data associated with the entity for which the footprint is being calculated. In this case, two $\mathbf{y}$ vectors were created, one each for the CABG and stenting procedures. These expenditure vectors were built by adjusting the disaggregated cost bucket data to exclude depreciation and direct salaries and wages. These transactions are accounted for elsewhere in the input–output tables from which $\mathbf{q}$ and $\mathbf{L}$ are derived, and their inclusion in the expenditure vector used to calculate the footprint for each procedure would inflate the results.

A single-region input–output table for the 2021–2022 financial year was built using the Australian Industrial Ecology Laboratory (25). This input–output table contained information on the economic transactions within and between 1,284 sectors across the Australian economy, and the associated greenhouse gas emissions generated by each sector during the year, drawn from Australia's National Greenhouse Inventory Report in line with emissions estimation rules adopted under the Paris Agreement (26). The full list of sectors in the Industrial Ecology Laboratory is given in the Supplementary material.

All greenhouse gases were included in this analysis, but adjustments associated with land use change were excluded.

3 Results—systemic carbon footprint of two cardiac procedures

For the 2021–22 financial year, 29 patients with stable two-vessel coronary disease underwent stenting, with an average total cost of $16,820 per patient, while 32 patients with the same diagnosis underwent the CABG procedure, with an average total cost of $73,211 per patient, 4.4 times that of the stenting procedure. Once expenditure on items not accounted for as a component of final demand within the input–output table was excluded, the average cost for those patients who underwent CABG was $38,196, 3.4 times more than that of the $11,150 cost for those who had a stenting procedure. Clinical decision making was according to physician and patient preferences. There were some differences of note in the internal cost allocation to cost buckets for each procedure, with, for example, the Specialist Procedures Suite cost bucket receiving the highest allocation for stenting (33%), and the Critical Care cost bucket receiving the highest allocation for CABG (21%). The two right-hand columns in Table 1 provide the percentage allocation of costs between cost buckets for each procedure.

From these data, we calculated that the carbon footprint associated with the average CABG procedure was 11.5 tonnes CO_2-e, 4.9 times greater than the carbon footprint associated with the average stenting procedure, at 2.4 tonnes CO_2-e. Figure 2 presents a comparison of these two footprint values, including a breakdown by aggregated sector. In both procedures, a significant portion of the carbon footprint is generated by expenditure on goods and services that were not directly clinical in nature, such as utilities, non-medical furniture and equipment, and services (40% for CABG and 48% for stenting).

Of note, emissions associated with waste for both procedures were calculated as part of the expenditure on the Utilities sector, since SLHD accounting does not allocate the expenditure on waste based on the physical quantities of waste generated by each procedure. Expenditure on waste collection generated a total of 26.1 kg CO_2-e for each CABG procedure, and 5.93 kg CO_2-e for each stent procedure.

Figure 2 also illustrates the percentage contribution to the total carbon footprint for each procedure, based on the aggregated economic sector to which expenditure was allocated. The sectors contributing to these aggregates are given in the Supplementary materials. Figure 2 shows some interesting differences between the two procedures, with the largest contributor to the carbon footprint of the CABG procedure being expenditure on consumable supplies (36%), while the largest contributor to the carbon footprint of the stenting procedure was expenditure on other manufactured products within the supply chain (18%). A review of the cost bucket allocations for the two procedures confirms this difference, with the Ward and ED supplies cost bucket allocated 13.4% of the total expenditure for CABG, but only 2.7% of the total expenditure for stenting.

IO financial information structure	SLHD Cost Buckets Codes															
	Allied	Med	Nurse	Critical care	Image	OR	Path	Pharm	Pros	SPS	Ward & ED supplies	Non-clinical	On cost	Excl	Covid	Pat trans
Pharmaceutical goods, for human use (excl wadding, gauze, bandages and surgical sutures)	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Surgical, medical equipment (excl X-ray) and appliances (incl artificial joints, limbs or eyes, pacemakers, mechanical dental chairs & needles or syringes)	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	0
Hydrogen, rare gases, nitrogen, medicinal gases (incl nitrous oxide and oxygen), carbon dioxide (incl dry ice) and carbon monoxide	0	0	0	1	0	1	1	0	0	1	1	0	0	0	0	0
Wadding, powder puffs, pads, cotton wool, gauze and bandages	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Catering services	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Laundry and dry-cleaning services	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Liquefied natural gas (other than from the well head)	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Electricity generated from fossil fuels	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Hydro-electricity	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Electricity generation nec	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Employers' liability insurance provision	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

FIGURE 1
An extract of the concordance used to connect the expenditure information provided by the SLHD and the financial information contained within the input–output table. A value of 1 represents a connection between the sector in the row and the sector in the column, a value of 0 designates no connection between the sector in the row and the sector in the column.

Analysis of the contribution made by each sector to the total footprint reveals that the most carbon intensive sector was utilities, which contributes 7.7 kg CO_2-e for every dollar spent on the sector across both procedures. This carbon intensity, along with that for the other aggregated sectors, is shown in Figure 3 for the activities associated with the CABG procedure. The carbon intensities for the activities associated with the stent procedure is shown in Figure 4. Pharmaceutical and other medicinal supplies was also a carbon intensive sector, contributing 0.54 kg CO_2-e for every dollar spent on the sector for CABG patients and 0.51 kg CO_2-e for every dollar spent on the sector for stent patients. The slight difference in intensity is due to the aggregated nature of the sectors presented, with a slightly different mix of contributing sub-sectors in each case. Supplementary materials show the carbon intensities for the contributing subsectors, these intensities have been derived from the EEIO model described in the methods section above. For the CABG procedure, costs allocated to consumable supplies influenced the total footprint value, contributing 4.1 tonnes per procedure (36% of the total). This included expenditure on supplies required to treat surgical wounds and was a relatively carbon intense sector, generating 0.49 kg CO_2-e for every dollar spent on the sector. For the stenting procedure, expenditure allocated to prosthetics (27% of total), in the aggregated medical and precision equipment sector, has a less significant impact on the total footprint, contributing 0.2 tonnes per procedure (8% of the total), driven by a lower carbon intensity for the medical appliances sector, at 0.07 kg CO_2-e for every dollar spent on the sector.

Our result equates to 0.14 kg CO_2-e per dollar spent on the stenting and 0.16 kg CO_2-e per dollar spent on the CABG, which aligns in scale with the sector wide intensity calculated by Malik et al. at 0.26 kg CO_2-e per dollar spent (4). The lower carbon intensity of the cardiac activities studied, compared to the national health care sector intensity, may be attributable to the selection of uncomplicated patient care episodes, which we did to allow a direct comparison between stenting and CABG. To put this carbon intensity in context, cardiovascular disease accounted for 5.4% of the Australian burden of disease in 2019–20 and the clinical response accounted for 6.28% of all hospital costs in 2020–21 ($8.8 billion) (27). Our initial research suggests that the 48,000 stent and 12,700 CABG procedures conducted in Australia in 2020–21 as part of this clinical response, have an associated carbon footprint that is of commensurate scale (27). The results discussed here are based on an annual sample for one major

Australian hospital. Further data sets from wider time periods and geographies would enhance the potential generalisability of these results. The timeframe considered in the study may not be entirely representative for a typical year, but it is likely that results prior or after COVID would be similar. Our results do demonstrate the application of the novel methodology proposed and provide a rich source of data for decision making within the studied context.

4 Discussion

Although there are unit process LCA studies of some of the individual aspects of patient care pathways (6, 12, 13), we believe that this is the first study to compare the carbon footprint of two common medical pathways adopted by clinicians to treat similar health conditions. The example of stable two vessel coronary disease was chosen *a priori*, as the clinical outcomes are generally very similar (19). We acknowledge that there may be subtle differences in post-procedure care over the subsequent years; up to 5–10% of stent patients might require re-intervention by 5 years, and there are some differences in medications (19). For example, stent patients more often require dual rather than single agent anti-platelet therapy for some months after the procedures; but CABG patients more often require anti-arrhythmic therapy. These can influence the comparative size of the systemic carbon footprints of these procedures, however these differences are likely to be very small, compared to the major peri-procedural differences informing the estimated carbon footprint (28). Given that, for these reasons, the choice of procedure is generally clinically equivalent, the choice between procedures exemplifies the type of instance where there would be a strong case for clinicians taking into account wider considerations such economic and environmental impact.

The magnitude of difference between the carbon footprints of each procedure quantified here, with the CABG footprint 4·9 times greater than the stent footprint, is to be expected to a certain extent, based on the relative difference in their costs, at 4·4 times. A more detailed review of the sector contributions reveals some additional insights however, with the much higher expenditure on ward and emergency department supplies associated with the CABG procedure influencing the relativity of these footprint values, effectively adding a carbon weighting to the difference in economic cost. The magnitude of difference between footprint results for these procedures indicates the potential contribution of environmental analysis, beyond clinical and economic considerations, in procedure selection.

Our results suggest that, in addition to the considerably lower financial cost associated with an elective stenting pathway, there was a considerably smaller systemic carbon footprint, when compared to a CABG pathway. Much of this reduced economic and environmental impact can be attributed to lesser requirements for post operative care. Usually, elective stenting will result in a post-operative overnight stay whereas post-operative care for CABG typically involves a 1–2 day stay in the Intensive Care Unit (ICU) and a further 5–7 day hospital ward stay (29, 30). Healthcare providers, patients, and health system administrators, seeking to work out the optimal treatment pathways, taking into consideration treatment outcomes, economic value, and a sectoral reduction in carbon emissions, could potentially draw on this evidence.

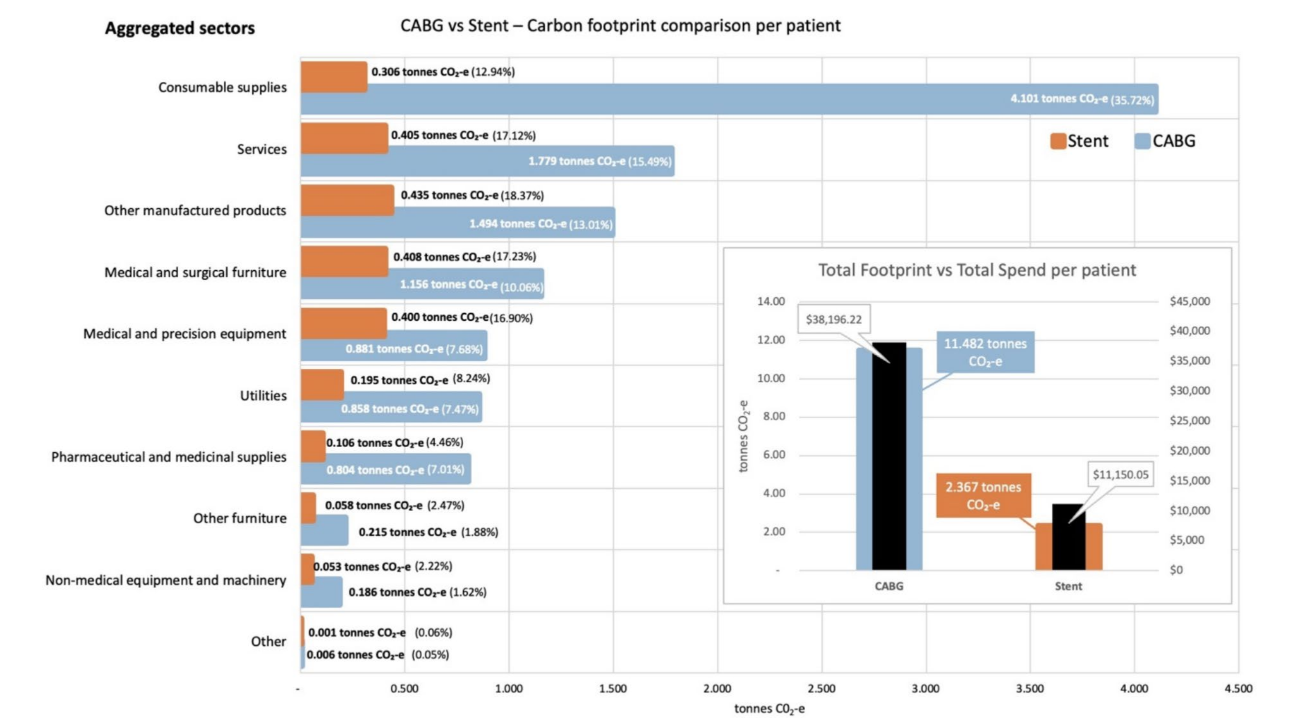

FIGURE 2
Carbon footprint contribution of each aggregated sector by weight and percentage for activities associated with CABG and stenting procedures, per average patient. Inset shows total carbon footprint and total spend for activities associated with each procedure, per average patient.

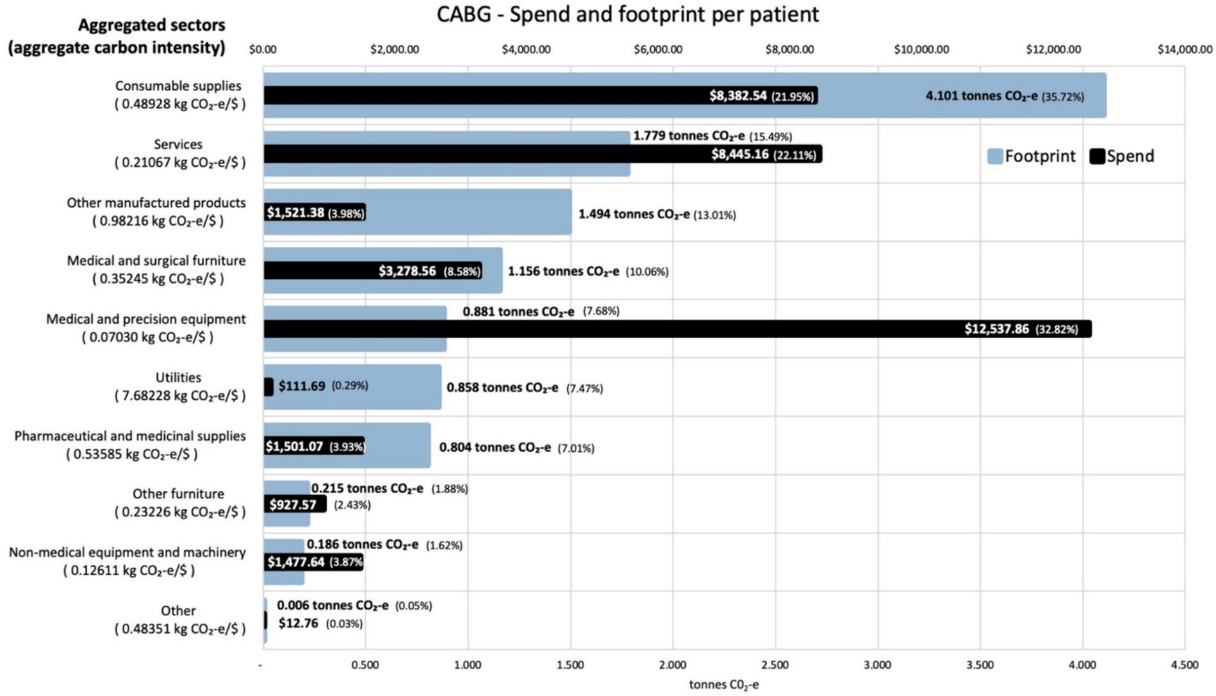

FIGURE 3
Carbon footprint contribution by weight and total spend in $ for each aggregated sector for activities associated with CABG procedures, per average patient. Carbon intensities for the aggregated sectors are given in the *Y* axis legend.

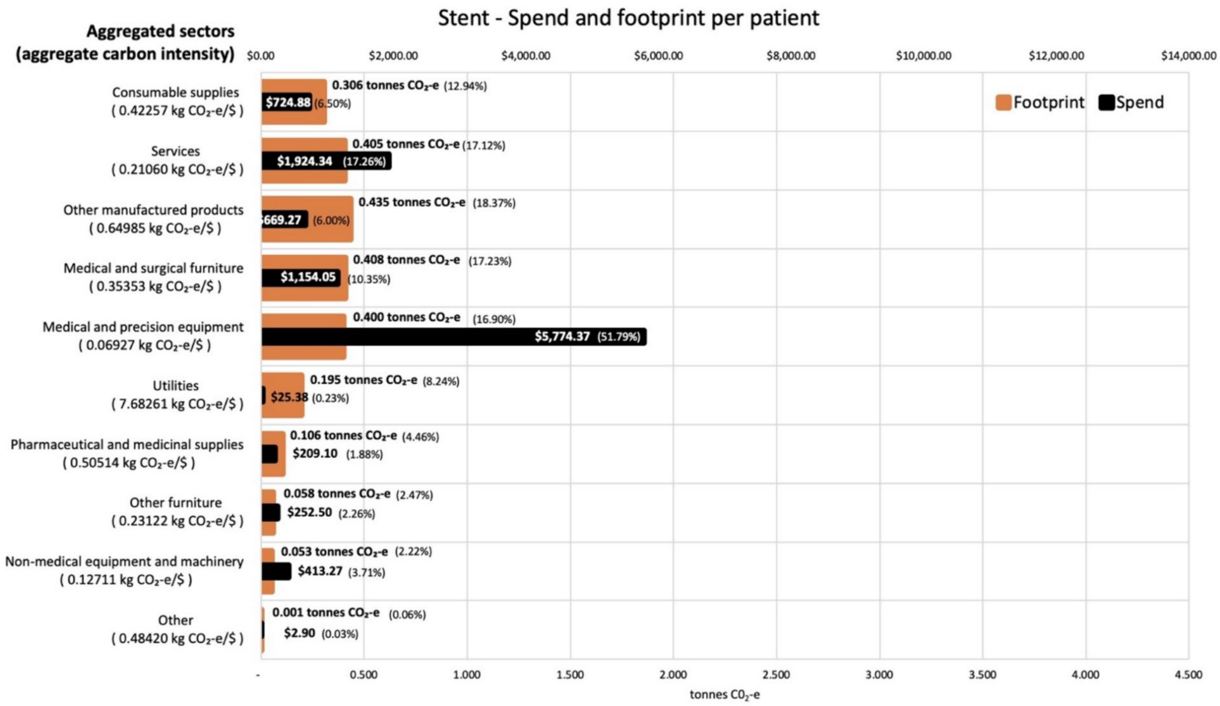

FIGURE 4
Carbon footprint contribution by weight and total spend in $ for each aggregated sector for activities associated with stent procedures, per average patient. Carbon intensities for the aggregated sectors are given in the *Y* axis legend.

4.1 Systemic and specific carbon footprints

EEIO analysis can be understood as connecting sectoral GHG emissions to the expenditure that supports each procedure, which we refer to as a systemic carbon footprint. This can be contrasted with the now widespread use of unit process LCA to quantify emissions associated with health sector processes to assess the associated environmental impacts (6, 12, 13). To ensure a manageable analysis, the boundaries in LCA studies tend to be relatively confined, barring an analysis of the complex systems that support patient care pathways. By contrast, the use of EEIO to quantify the carbon footprint associated with these two cardiac procedures supports a boundaryless, systemic assessment of the total carbon emissions generated to support the delivery of these procedures at RPAH. These footprint results incorporate the whole of system emissions attributable to a procedure, including the emissions associated with operating the healthcare system and its facilities, infrastructure, and personnel, along with the apportioning of utilities, transport, and material inputs such as clinical supplies and medical devices and furniture.

The systemic scope of inclusion for EEIO analysis is highlighted in Table 2 when we compare our results with two other recent analysis of cardiac procedure carbon footprints. The 124.3 kg CO_2-e emissions calculated by Grinberg et al. for conventional adult cardiac surgery in France, used an eco-audit approach (31). This simplified LCA approach may have impacted on the precision, robustness, and representativeness of their study (35). A subsequent LCA based estimate of the amount of CO_2-e produced by CABG surgery at Tufts Medical Center was four times larger, at 505.1 kg CO_2-e per case (33). However, some of this difference may also be attributable to differences in the procedure, like Tuft's requirement to autoclave all waste from cardiac suites, prior to disposal. Nonetheless both these results were well within the 6–814 kg CO_2-e range identified by Rizan et al. in their systematic review of surgical operation carbon footprints (36). The very significant difference between the footprint calculated by Grinberg et al. (31) and Hubert et al. (33), and our result of 11.5 tonnes CO_2-e for the CABG procedure, suggests that a narrowly bounded focus on specific surgical or other clinical processes runs the risk of very significantly under-estimating the systemic carbon footprint of patient care pathways, by excluding the emissions associated with the operation of the health system and the comprehensive supply chains that support a particular procedure. For example, Grinberg et al. (31) only included disposable medical products, pharmaceutical products and electricity consumption used in anaesthesia, cardiopulmonary bypass and surgery. Similarly, Hubert et al. (33) estimated by collecting data from anaesthesia, electrical consumption, and generation of solid waste. They acknowledged that emissions from the heating, ventilation and air-conditioning (HVAC) system, reprocessing surgical instruments, pre and post-operative care were excluded. Neither study included a range of other sources of emissions in the patient encounter included in our study, including pathology, critical care, patient transport, as well as non-clinical sources.

The difference between the results in Table 2 is superficially striking. However, these studies have quite substantially different scopes. The American and French LCA studies are designed consequentially, aiming to quantify the marginal additional climate change burden of the CABG procedures studied. By contrast our EEIO study can be understood as an attributional life cycle assessment, aiming to quantify the contribution of the patient care pathway associated with a CABG procedure in Australia to the overall burden of green-house gas emissions driving global heating. The difference between the footprint calculated by Grinberg et al. and Hubert et al. for conventional isolated cardiac procedures and our calculation for a CABG patient care pathway may, at least partially, be explained by these different scopes (31, 33). The scope of our calculations include the full range of activities contributing to each patients' episode of care from admission to discharge. This includes allied health services, medical support, nursing, critical care, imaging, pathology, prosthetics, specialist procedures, ward and emergency department supplies, non-clinical and on-costs, and patient transport. Importantly, the pathway for a patient undergoing a CABG procedure typically involves an extended period of post operative care prior to discharge, consuming up to 9 days of hospital resources (28, 29). The consumption of these resources all contribute to the carbon footprint of a patient care pathway, but are not within scope for the LCA studies here discussed. All these essential aspects of delivering a cardiac procedure contribute to the health sector's overall emissions, some 7% of Australia's total emissions (4).

4.2 Potential applications of systemic footprints

In making recommendations to patients, healthcare providers have, to date, been almost exclusively influenced by the clinical outcomes of procedures. Increasingly, however, they are acknowledging that treatment choices also have economic and environmental consequences and, in the face of the climate crisis in particular, that environmental impacts also form an important component of healthcare decision making, including informing patients (37, 38). In this context, data about carbon footprinting of different procedures are essential to help healthcare providers understand the environmental impact of their clinical choices.

In this paper, we chose two procedures with relatively similar clinical outcomes, recognising that this is the circumstance where healthcare providers will be most interested in other impacts of their decisions, including those on the environment. There are many other examples in medicine where there are two or more choices for clinical care with similar outcomes, for example in the choice of asthma puffers (pressurised with propellants versus activated by inhalation), anaesthetic agents (intravenous versus volatile gases), bariatric surgery versus GLP-1 agonists for weight loss, and alternative forms of peritoneal dialysis. Such equipoise cases represent relatively uncontroversial entry points for guiding medical practitioners to consider differences in emissions profiles in their advice. Cases where emissions profiles are in tension with health outcomes will require far more public debate, but it can be anticipated that as the impacts of climate change become more severe, debates in health care will, as in other areas of public policy, need to more seriously consider climate impacts.

In addressing climate change impacts, healthcare planners will also benefit from a streamlined mapping of emissions hotspots across patient care pathways, made possible by the systemic carbon footprinting approach demonstrated in this paper. These hotspots can inform systems design for emerging primary care models in areas

TABLE 2 Comparison of three different CABG carbon footprint analysis.

Study	Method	Cohort	Scope (per procedure)	Data	Result (kg $CO_2 - e$)
Grinberg et al., 2021 (31)	Eco-audit, using granular primary activity data. Single site study.	Single valve repair or replacement and isolated on-pump coronary artery bypass grafting in adults at Lyon University Hospital, France. ($n = 28$)	Surgical, anaesthesia and the cardiopulmonary bypass workstations. Disposable medical products, pharmaceutical products and electricity consumption.	Based on a bill of materials, process choice, transport requirements and duty cycle (the details of the energy and intensity of use), and disposal route. Considers the embodied energies and process energies from a database of material properties; those for the energy and carbon intensity of transport and the energy sources associated with use are drawn from look-up tables (32).	124.3
Hubert et al., 2022 (33)	LCA, using granular primary activity data. Single site study.	Uncomplicated CABG surgery for elective patients at Tufts Medical Center, USA ($n = 18$)	The surgical suite, defined as the sum of a hospital's operating theatres, surrounding corridors, and sterile core, inclusive of anaesthetic and equipment rooms but exclusive of pre-operative and post-operative holding and recovery areas, administrative offices, and medical device reprocessing departments. Staff travel was excluded as it was considered outside of the study boundary (33).	Data were collected on volatile anaesthesia utilisation, electrical consumption, and generation of solid waste based on both trash bag collection and weights of the sharp container. Following GHG Protocol, considers scope 1, anaesthetic gases using Global Warming Potential (34); scope 2, electricity use (grid intensities provided by local electrical utilities), energy for space heating; and scope 3, surgical supply chain and waste disposal, applying DEFRA greenhouse gas life-cycle conversion factors for waste disposal, which take into account greenhouse gas emissions generated upstream in the supply chain as well as in the downstream disposal (33).	505.1
This study	EEIO, using averaged patient activity-based cost data. Single site study.	Coronary artery bypass using 1 LIMA graft and coronary artery bypass using 1 saphenous vein graft for stable, non-diabetic patients with two-vessel coronary disease at RPAH, Australia ($n = 32$).	Full patient encounter (admission to discharge). Operation of healthcare system and facilities, infrastructure, and personnel, along with the apportioning of utilities (including waste), transport, and material inputs such as clinical supplies and medical devices and furniture, excluding capital items.	Cost data for NHCDC for the financial year 2021–22 (Round 26) for costs incurred by Royal Prince Alfred Hospital (RPAH). Single-region input–output table using the Australian Industrial Ecology Laboratory for 1,284 sectors across the Australian economy, and the associated greenhouse gas emissions generated by each sector during the year, drawn from Australia's National Greenhouse Inventory Report.	11,482

such as telehealth, introducing consideration of carbon emissions into analysis of health care delivery reform (39). Research in other sectors has shown that integrating activity-based costing evaluation and carbon footprint assessment can help managers incorporate environment costs into decision-making processes (40, 41). The method we describe may achieve similar results in informing health systems funding allocation, by providing planners with a carbon weighting to include in their activity-based funding determinations.

Operationally, hotspots identified through EEIO analysis will also constrain parameters for process-based LCA, allowing targeted collection of granular data to inform very specific LCA studies. These studies can be costly, but when targeted, can provide detailed guidance for refining facilities design and management, and for the refining clinical procedures, in areas such as waste management and alternative clinical technologies.

4.3 Sources of uncertainty in systemic footprinting

In their study of the carbon footprints of hospital care pathways Zhang et al. (14) conduct a data quality assessment of emissions factors and financial activity data like those used in this study. They found these to be 'good' or 'very good' in all aspects, although the framework they used is typically applied to physical data. Pertinently, recognising that Leontief's basic input–output relationship cannot be differentiated analytically, Lenzen (42) describes a range of uncertainties associated with input/output analysis and compares these to truncation errors associated with standard unit process life cycle techniques. He notes that cumulatively, these uncertainties are smaller than the truncation errors for most commodities, and that this uncertainty decreases with the number of components in the assessment. We note that the number of components in our assessment of patient care pathways defies conventional unit-process assessment, suggesting a lower level of uncertainty. In a later paper Lenzen et al. (43) undertake a comprehensive uncertainty analysis to estimate standard deviations for carbon multipliers used in the calculation of the UK's carbon footprint, using Monte Carlo techniques. They conclude that multipliers for consumer emissions exhibit relatively low Relative Standard Deviations of between 3.0 and 5.1%.

The contrast between the results of LCA studies of the carbon footprint of cardiac procedures and the EEIO study described here emphasizes the difference between these modelling approaches. Each has some limitations. Aside from the major difference in scope, limitations associated with these different methods may contribute to the contrasting scale of results. Unit process LCA, informed by detailed physical data, and EEIO, informed by financial activity data, are subject to different uncertainties (42). LCA studies typically suffer from some degree of truncation error, as they are unable to comprehensively map their entire supply chain. This has been estimated to lead to a more than 50% underestimate of emissions. Studies of more service based activities, such as those in healthcare, tend to have higher truncation errors (42). The degree to which more sophisticated LCA techniques address this limitation continues to be debated in the literature (44, 45). By contrast, EEIO provides a boundaryless and therefore comprehensive account of supply chain emissions, but is limited in the level of granularity that can be achieved given its comprehensiveness. The activity-based costing data used for estimating the footprint of an activity has been subject to several accounting transformations that may also contribute to uncertainty.

Bearing in mind both the different scopes and uncertainties associated with these distinctive modelling approaches, it is important to recognise that they are useful for different purposes: EEIO provides a comprehensive systemic footprint (which could inform strategic decision making such as health systems design and guidance on choice of patient care pathway), LCA provides a detailed specific footprint (which can inform tactical decision making). While unhindered by the need to select a boundary, limitations are introduced to any EEIO analysis through the sectoral resolution of the underlying input–output tables, providing far less granular data than the primary data collected for LCA studies. An EEIO analysis will not provide guidance on procurement decisions between alternate suppliers of goods and services, if they are in the same sector. It will also not provide detailed guidance for refining facilities design and management (for example optimising HVAC, or power standby) or for refining clinical care procedures (for example sterilisation and reuse rather than single use of clinical supplies). Further, specific to the health sector, some authors are cautious of distortions in costing, for example resulting from different drug pricing regimes, that may make it difficult to accurately connect different expenditure values to the resultant GHG emissions (13). Although the subsidies that potentially cause these distortions are incorporated into the input–output tables upon which EEIO analysis is based, these concerns do bear further investigation.

Other limitations of the methodology presented here are introduced with the high level of aggregation used in allocating the costs associated with each procedure to cost buckets, since these data need to be disaggregated to match the economic sectors present in the input–output table. This disaggregation process could be improved if more detailed insights were available on the allocation of detailed costs to each cost bucket, or if cost data were available at a finer resolution, such as at the cost centre level. Further studies using more highly disaggregated activity-based costing data are underway to understand the impact of this limitation.

Finally, the exclusion of depreciation costs is recognised as a limitation of the described method. This exclusion resulted in an underestimate of the systemic footprint, which did not include emissions associated with expenditure on capital items. This does warrant research into practical approaches to estimating capital systemic footprints. Further studies are underway, to explore the implications of these methodological differences and to establish guidelines for the contexts in which the different methodologies will be most appropriate.

5 Conclusion

Clinical guidance on the management of coronary disease has, to date, been silent on consideration of carbon footprints. As Tennison et al. comment in their carbon footprint assessment of the NHS, "The selection of a less carbon-intensive and resource intensive care practices where clinically appropriate can reduce both emissions and costs" (3 p.e90). Our results suggest that an elective stenting pathway has a substantially smaller systemic carbon footprint compared to a CABG pathway. Given clinical equipoise in the specific circumstance we have described, guidance on clinical decisions regarding treatment of stable patients with two-vessel coronary disease could consider both the economic and environmental costs, and thence recommend stenting.

This study demonstrates that clinical decision making can be informed by systemic carbon footprint analysis, to be considered alongside health care outcomes and economic indicators. In this way comparative estimates of systemic emissions attributable to different patient care pathways can contribute to the evidence base informing health care policy. EEIO analysis is a tool that is useful in this context because the activity based costing data required to conduct the assessment are readily available in Australia and many other jurisdictions (21), allowing cost effective and rapid analysis.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Sydney Local Health District Ethics Review Committee (RPAH Zone). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

FS: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. AI: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RZ: Data curation, Formal analysis, Software, Writing – original draft. LH: Data curation, Investigation, Writing – review & editing. DJC: Conceptualization, Funding acquisition, Writing – review & editing. DSC: Conceptualization, Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1386826/full#supplementary-material

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Building competency to deal with environmental health challenges: experiences and a proposal

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The global landscape of professional training in environmental health, encompassing ecological public health or environmental public health, lacks consistent global implementation for training programs for public health practitioners, clinical professionals, and individuals across various disciplines, as well as standardized curricula for undergraduates. This training gap is related to the overall lack of capacity in addressing the population impacts of the triple challenge of pollution, biodiversity loss, and climate change, impeding the worldwide transition to and development of ecological sustainability. This paper reviews existing approaches and their potential to address implementation challenges within the necessarily tight timescale. Spreading of best practice appears feasible even without substantial additional resources, through the reorientation of current practices via comprehensive multi-disciplinary training programs. By adopting international best practices of training in environmental health, the focus in training and education can shift from future decision-makers to enhancing the competencies of current professionals and their institutions.

KEYWORDS

environmental health, public health, ecology, professional training, education, ecological sustainability, environmental change, ecological public health

1 The role of education and training in environmental public health (EPH)

1.1 Introduction

Human societies face a triple challenge of pollution, loss of biodiversity and climate change, that combine to produce current and expected future adverse social and health impacts (1). These trends are not restricted to Western societies but appear to accompany any drive to development in all continents and managed by the whole range of available political arrangements (2, 3). The numerous calls for a change of direction and transformation have produced limited impacts, leading to inadequate rate of change accompanied by rather frantic attempts to either deny the need to act or last ditch attempts to draw on moral foundations for change in the absence of realistic avenues for a transition to ecological sustainability of human societies. Although a response from educational specialists is expected to address the need of future generations, this would be insufficient by itself to achieve a conversion within the time period expected to be required. This paper outlines a practical element of societal response with a realistic chance of contributing to widespread adoption of relevant activities: training aiming to empower those currently employed who would wish to engage with the process of change toward ecological sustainability, associated with an institutional affirmation of legitimate remit that permits such activity as widely as possible.

The overarching questions which must be borne in mind while envisaging provision of any training or educational program are the following three. According to the overall framework mentioned in the companion paper to this (4), we are also providing our perspectives that might benefit from a comprehensive and open discussion, not only in academia but also with policymakers, businesses, trade unions, public and private health organizations, and community-based civil society groups.

1. What are some key objectives this training will achieve? Our answer: topics will be similar for all target communities, but specific objectives will vary by the target community.
2. What target communities? Our answer: (a) practitioners of public health (specialists); (b) other practitioners who have a part-time commitment to public health (PH) (e.g., family doctors, engineers, architects, environmental scientists, and several others); (c) postgraduate students who are not practicing either public health or any other profession, but intend to develop a capacity to do so.
3. What type of training? Our answer: problem-based learning directed at an appropriate level to a target audience; health services, public health, and prevention are matters that involve many disciplines and competencies (see section 4.2 and 5).

According to WHO (5), a particular attention must be paid to those working in environmental management/sustainability professions to enhance their knowledge of health/PH/EPH—focusing on the health impacts of their efforts, so also align to the EPH goals such as adoption of paradigms appropriate to the challenge (4).

Health professionals can drive social and policy change (6) as they are generally highly trusted (7) and have influence at all levels of society. With trust comes the responsibility to influence wisely and lead effectively, which requires collaborative engagement beyond individual actions (8), thus "Health professionals will be called on to engage as humble, informed, and trusted partners in the collective, boundary-crossing effort of transforming practices and structures to better sustain the health and wellbeing of all life, including our own" (9).

Such professionals should be educated and trained in the perspective of sustainable development and the green economy through public health management and risk assessment. They should be exposed to public and urban health issues, which are fundamental issues for well-being and environmental aspects at any level. Matters relating to pollution, in general, are essential for actions addressing infectious and chronic-degenerative diseases, while in urban health; the themes of strategic planning are fundamental concerning the healthiness of urban environments and possible adverse health effects.

Last but not least it is essential to integrate climate and planetary health into all general education and training of PH professionals as well as allied health professionals (10).

According to Barondess, "Professions are complex social structures derived from the guild system of specialized competencies intended to organize specialized and complex bodies of knowledge in such a way as to address both individual and societal needs. These are the basis of a social contract enfranchising the members of a profession. It makes professional knowledge central to the wellbeing of today's society" (11). Inter-disciplinary work of health and other professionals is needed to improve delivery of ecologically sustainable societies.

The field of professional training for environmental health, whether called ecological public health or environmental public health, lacks consistent implementation globally of training programs for practitioners of public health (12), clinical medicine (13), and other disciplines, as well as educational curricula for undergraduates (14). Overall, the training effort is inadequate with reference to the triple challenge of pollution, loss of biodiversity, and climate change (15). This impairs the transition to ecological sustainability of communities globally.

The goal of the present paper is to highlight that several existing approaches and experiences represent a tangible demonstration that the most common barriers to implementation may be addressed, even in the absence of significant additional resources, by re-orientation of current practice through training of practitioners. Adopting best practice available internationally in this area, would shift the focus in training and education from the responsibilities of future decision makers and professionals, to those of those currently in post. In alignment with these objectives, Appendix A (see Supplementary materials) offers a practical context by delivering a comprehensive analysis of various field experiences conducted at both national and international levels within the sphere of education and training.

1.2 The role/task of EPHT and HIA

The role and task of Environmental and Public Health Tracking (EPHT) and Health Impact Assessment (HIA) is to integrate understanding, evaluation, professional profiles, and institutions (including tools). EPHT has the potential to serve as a concrete tool to "…improve the effectiveness of adaptation and mitigation strategies, assess progress toward nationally and internationally agreed targets, act as an early warning system, and hold decision-makers accountable.

TABLE 1 Examples of environmental health indicators within the DPSEEA framework.

Concern: causal chain		Housing-related indicators	Microbiological indicators (water contamination)
Driving force	Type of development or human activities	Migration	Sewage generation
		Life conditions index	Water pipe deterioration (aided by embargo)
Pressure	Amount or size of production	Housing quality	Amount of waste produced
		Water supply	Amount of untreated effluent
	Emissions	Sanitation facilities	% of broken sewage lines
		Liquid and solid wastes	
State	Environmental effects	Microbiological contaminants	Coliforms in water, food
		Standing water (vector breeding)	
		Pests, rodents, and pathogenic organisms	
Exposure	Human exposure	Proportion of households/people exposed to pests, rodents, and vermin	Estimated exposure to contaminated food/water
			Serum analysis for Hepatitis and typhoid
	Dose	Parasites in stool	Feces for cholera, Shigella
Effects	Early effects	Diarrhea, fever	Diarrhea, fever, and nausea
		Gastrointestinal diseases, parasitic	Cholera, Hepatitis A, typhoid, dysentery, and gastroenteritis
	Late effects	Leptospirosis	Death from dehydration
	Death due to:	Death from dehydration	
Actions	Interventions can be identified and associated with each level of DPSEEA framework		

Source: Modified from Yassi (20).

Indicators for inclusion in the system should be prioritized using transparent criteria, including relevance, sensitivity, sustainability, scalability, accuracy, economic viability, and consistency" (16). It has been defined as: "The ongoing collection, integration, analysis, and interpretation of data about environmental hazards, exposure to environmental hazards, human health effects potentially related to exposure to environmental hazards. It includes dissemination of information learned from these data and implementation of strategies and actions to improve and protect public health" (17).

It is an approach that helps to increase the understanding of environmental public health and global health, improve comparability of risks between different areas of the world, and enable transparency and trust among citizens, institutions and the private sector, and inform preventive decision-making.

Environmental and Public Health Tracking is also a helpful tool for strengthening the established Driving Forces, Pressures, State, Exposures, Health Effects and Actions (DPSEEA) framework (18). EPHT promotes a systematic integration of the DPSEEA components above-mentioned, taking environmental and health parameters into account. For each stage of this scheme, one can design and/or evaluate indicators to measure the impact of interventions at each level (19). An example from Cuba (Table 1) shows that an ecological approach to environmental health has been applied decades ago, and the DPSEEA framework may clarify requirements of public health surveillance/EPHT in relation to specific interventions/actions (20).

Environmental and Public Health Tracking aims to promote a resilient society by analyzing complex datasets, addressing different audiences, and supporting environmental health messaging tailored to each audience:

- The public: information to support individual changes in attitudes and collective actions.
- Professionals and stakeholders: tailored information to health professionals, land planners, urban planners, environmental managers, policy makers, and researchers.
- Decision-makers: integrated health and environmental information to inform decisions and create opportunities to reduce the multiplicative impacts of rapid urbanization, globalization, and climate/social/economic change (21).

Such general and generic categories also include resource managers, planners, economists, conservationists, indigenous and locally impacted communities, community developers, and other essential stakeholders. They are all strategically important, taking into proper account the dynamics that interrelate the two central issues on how population health may be improved: individual behavior and social and economic factors (22, 23). A conceptual framework to integrate economic and other dimensions for ecological public health facilitates identification of appropriate interventions (24).

The EPHT approach strives to achieve its vision of "*Healthy Informed Communities*" by empowering environmental and public health practitioners, healthcare providers, community members, policymakers, and others to make information-driven decisions that affect health while maintaining appropriate data protection measures (17). Several technological applications have become available (25, 26) or present considerable promise (27) that can support EPHT operations by a range of stakeholders.

In this context, Health Impact Assessment (HIA) has been proposed as the combination of methods to support Health in All Policies (HiAP) implementation by providing scientific evidence on the positive and negative effects that any new program, project or proposal may have on health and health equity.

The availability of evidence is often perceived as consistently insufficient when making decisions related to various aspects of public health, encompassing emerging issues and interventions' risk–benefit assessments. In practical terms, decisions must align with current resources and tangible budgets, prompting consideration of an alternative analytical approach known as "decision analysis." This approach operates on the premise that decisions are made amidst incomplete knowledge, and not all pertinent facts are accessible for prevention assessments. In essence, the strategy for prevention involves choosing between interventions, each with associated costs and benefits. Comparing two alternative choices, A and B, directed at the same prevention goal allows the establishment of a ranking based on their cost–benefit ratios. This approach facilitates the comparison of knowledge supporting different choices in terms of their overall health impact.

The decision analysis employs multi-criteria decision analysis (MCDA), a methodology applicable to risk prioritization, especially in national decision-making. While other methods, such as cost–benefit analysis (CBA) and cost-effectiveness analysis (CEA), focus on economic considerations, MCDA accommodates a broader range of criteria, including qualitative and quantitative evidence. As we navigate global challenges, the call for "new coalitions and partnerships across many disciplines" is imperative. The ultimate goal is a comprehensive integration within a "planetary" framework, addressing environmental and public health outcomes. This perspective underscores the necessity for a global outlook in delivering ambitious objectives (28–30).

In summary, EPHT is an instrument that can support the cross-sectoral integration of information to assist decision-making in support of the utmost ambitions for global and planetary health outcome.

The core infrastructure of EPHT within national public health agencies can deliver both capacity to support ongoing concerns on hazardous pollutants and chemicals in drinking water, land, food and air and new perspectives on the central value of ecological and social factors in affecting health and wellbeing in the course of multiple transitions currently experienced by society (21). The latter perspectives are explored initially in research partnerships between national public health agencies operating EPHT programs and academic or other relevant research institutions.

This process means EPHT may support mainstream public health operations and partnerships in transitioning toward more appropriate consideration of ecological and social factors in health protection and health improvement activities (31).

1.3 Experiences of integrated training across the world

We have worked with several professional networks of which we are part to review experiences in training and education of professionals that have a role in advising decision makers about human activities with known impacts on public health, identifying those training activities that aimed at re-orientation of a human activity toward ecological sustainability. We have extracted from a purposeful selection of experiences those elements that could contribute to recommendations for general application in comparable contexts.

Core elements of what constitutes good public health practice have a strong focus in a curriculum, so that public health trainees will have an opportunity to demonstrate in their actual service both the confidence and competence necessary to go on to develop increasing levels of expertise in their subsequent, more specialized professional practice. Further details of country-level as well as supra-national experiences have been collated and are presented in Appendix A. There are cultural, disciplinary, institutional and economic types of obstacles in developing, running and completing training programs that address the issues highlighted. The fact that several experiences have already been completed means that objections to this approach can be overcome in practice, giving rise to an expectation that such practices can be extended each within its milieu and beyond.

Public health trainees and others involved in learning about their role as a public health agent are expected not only to know about good public health practice and show they can do it or apply it in a protected setting, but, over the length of the training program, to undertake and do their daily work with required levels of knowledge and understanding and at increasing levels of complexity. The Miller Triangle has been used to illustrate the three phases of any health training program, moving from learning through formal study (phase 1), to learning from service experience and increasingly complex service work (phase 2), to demonstration of integrated practice of complex competencies (phase 3) (32). This approach has been widely used for the assessment of professionals in health care, clinical and scientific/technical (33), and has been extended to application of ecological determinants of health by public health professionals (34).

To achieve the desired social and health benefit, a participatory approach in design and interpretation of EPHT or surveys or other activity intended to support or implement public health interventions has been recognized as crucial (35). Three broad disciplinary areas are thus put in relation with each other: natural/biophysical sciences, epidemiology, and social sciences (Figure 1). The shared goal of ecological sustainability of a community may not be achieved when excessive focus is placed on only one or two of these.

The educational theories that have underpinned effective integrated training often include problem-based learning, using engaging tasks or problems as a starting point for self-directed and self-regulated learning, thus encouraging trainees to express and share with others their skills, experience and knowledge (36). Training methods can then be broadly interpreted and include role play (37), field visits, leading to experiential and masterly learning, participatory and deep learning. Case studies provide an effective learning setting to incorporate different learning models with the purpose of developing a set of practice-oriented skills, via mobilization of cognitive and psychomotor participants' skills, values, attitudes, and feelings (38).

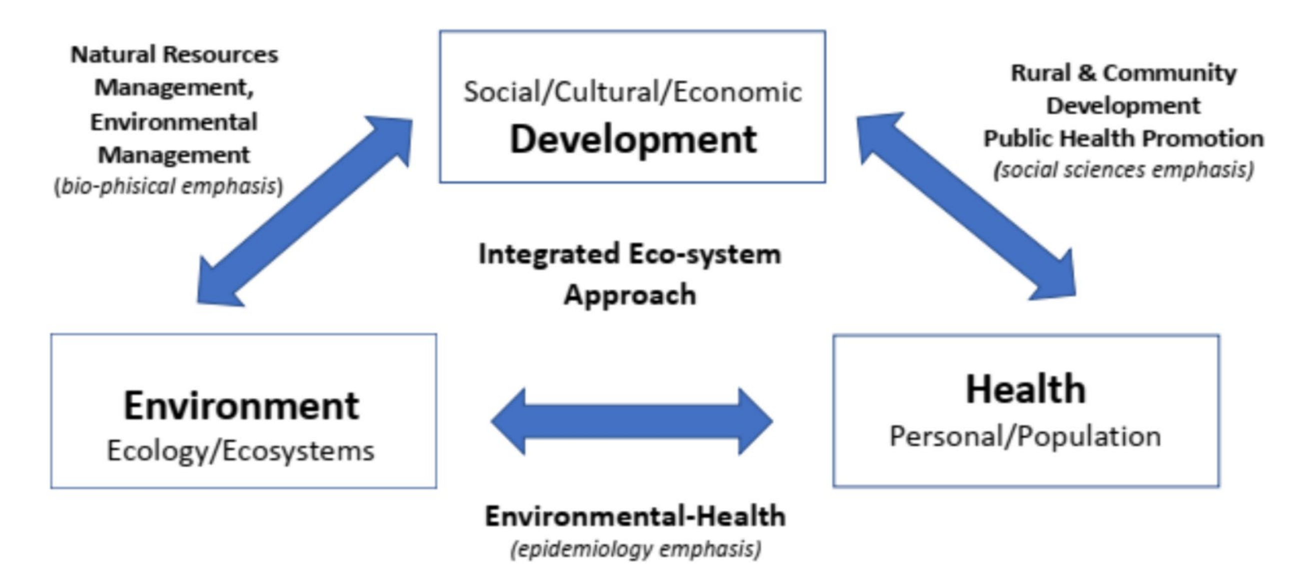

FIGURE 1
The "HEAD" (Health, Environment, and Development) triangle: links between different disciplinary territories. Source: Parkes (35) (modified).

TABLE 2 Elements of proposed curriculum for training to build capacity in Environmental Public Health.

General concept area	Themes
Environmental public health functions with specific goals to be defined and achieved in partnerships with local communities, health and social care services, and professional/scientific societies	*Intervention-building approaches (including cost–benefit analyses)*
	Evidence reviews for policy/decision makers
	Risk assessment, risk management, risk communication
	Environmental public health tracking/Health impact assessment or analysis
	Response to events and preparedness
Population thinking: "a mode of conceptualizing issues for a whole group of people defined in a certain way."	*Ethical, cultural, social, policy aspects*
	Defining populations over time
	Measurement (including exposure science)
Group Comparison: "contrasting what is observed in the presence of activity/exposure to what would have occurred had the group of interest not been exposed to the postulated cause."	*Study designs*
	Use of modern statistical analysis methods
	Causal inference

2 Proposals for training and education in environmental public health

2.1 Preparing the current workforce (retraining and continuous professional development)

2.1.1 Overall approach

The imperative to fortify environmental health curricula arises from global challenges encompassing chemical exposure, ecological shifts, and climate change, posing intertwined social and health impacts (39). Seven pivotal developments in environmental public health emerge in response to these challenges: occupational and environmental health, political ecology of health, environmental justice, eco-health, One Health, ecological public health, and planetary health (28). While each development holds value, certain limitations exist. For instance, the One Health framework, though addressing the triple challenge, tends to emphasize human and animal health over environmental drivers. Recognizing the urgency of the environmental public health task, we propose a pragmatic approach—integrating environmental and ecological considerations into existing curricula rather than creating separate ones. This approach necessitates a philosophical shift in perspective but requires only a minor adjustment in professional skills and competences (40). A framework for curricula that we propose could help standardize training of any practitioner in developing competences expected to be beneficial to EPH is presented in Table 2, however based on the criteria and recommendations in this paper other frameworks may be equally valid. Several specific topics and case studies have been identified for each of the themes listed, but these would differ by type of practitioner and cultural/disciplinary/institutional context.

Given the urgency, focusing on training the current workforce becomes a priority. This calls for a recognition that a new remit within existing domains can be admitted professionally and legally. The experiences shared in this paper aim to encourage other countries to review and approve similar curricula, seeking legal recognition for professional practice. Acknowledging the diverse roles within this broader public health field—public health specialists, those indirectly involved, and professionals aware of public health implications—requires separate curricula tailored to their specific needs.

As illustration of such wide range of roles, an example will be given for each of these three groups.

2.1.2 Public health practitioners

Typical aspects of the role of a public health specialist are: (i) Population thinking (in relation to exposure, drivers etc.); (ii) Interpretation of health data (in relation to eco-social and other factors); (iii) Identification of causes susceptible of primordial prevention. Professional activity in public health has been shaped by challenges that point to the need to adopt a population perspective in assessment and management of multiple issues. Communicable and non-communicable disease each have been addressed by development of a set of competences adopted by most countries. Recognition of the environmental drivers, pressures, states, and precursors of each type of disease facilitates matching with appropriate interventions available at each level to minimize and prevent disease.

Therefore, a public health specialist working on environmental public health could be trained in each country, by provision of a curriculum integrated with existing professional competencies and remits. Such curriculum could be broad to include competencies to address pollutants (41), and ecological aspects (42), as well as climate aspects (43) in relation to health, as needed to address co-existing drivers across these themes. Overall, the lessons from countries and settings reviewed here, point to the feasibility of such enterprise elsewhere. A committee comprising staff from national public health and professional societies of practitioners could complete the process of establishing a curriculum inspired by experience of others, but tailored to the local needs and priorities (Table 3).

2.1.3 Health care workers

The importance of the health care workers has been paramount all around the world even before COVID-19 pandemic. Societies are aging, health spending is rising in response to more complex health needs. The rapid spread of COVID-19 added complexity but provided essential lessons, which should be considered either in terms of resources to be allocated or in terms of the systematic approach, which should be comprehensively implemented in Public Health care.

Also connecting Primary Health Care (PHC) and occupational health (OH) is critical for better prevention of chronic conditions (such as musculoskeletal or mental health disorders) that lead to absenteeism or early departure from the labor force (44). Initiatives for better protecting workers' physical and mental health could include raising awareness among managers, improving the physical working environment, humanizing social relations at work, and offering programs dedicated to encouraging disabled people to return to work. Equally important is the health surveillance of workers, through assessing and responding to mental stress and physical strain at work.

As such it is essential to remember that only a real integration of PHC, Prevention and Hospital care could create the condition for a multidisciplinary workforce which play a vital role in recognizing and managing the environmental and social factors that affect community health.

Health systems can participate in this movement by adopting two critical roles: working as "anchor institutions" to support local problem-solving efforts and serving as partners in innovative approaches to safeguarding community mental health.

In addition, PHC are the frontline of community wellbeing, and therefore can have an important role in community building, social cohesion, and resilience. COVID-19 emergence highlights the need to place such strengths at the forefront of any emergency plans, as these can help align solutions that the current and more general climate crisis demands with a compelling vision of local well-being and participation (Table 4).

The key tasks for health care workers to contribute to ecological public health are:

- Encouragement of decisions toward health care systems that maximize resilience to disasters and are ecologically sustainable.
- Advancement towards a resilient approach to address global threats at the local level.
- Integration or at least networking among all facets of health practice (i.e., PHC, Prevention, and Hospital).

2.1.4 All others (using examples of architects and town and country planners)

There has been a recognition of the need to consider social and health impacts as an indicator of the ecological sustainability of activities in sectors different from health; for example, town and country planning and built environment, and also agriculture and forestry, transport, education, military and civil protection (see Table 3) (45).

Although the example of town and country planning and related built environment topics is described here, a similar graded approach is promoted in all the sectors (Table 5).

TABLE 3 Several levels of depth at which the training of practitioners in public health may be appropriate.

Audience within public health	Level of training	Mode of training
A. Decision makers in public health would have remit for district-level budget and operational decisions.	A few hours	Online 100%
B. General public health workforce may require an overview of the topics and access to appropriate subspecialists, able to chair working groups on specific themes, brief decision makers.	A few days	Online 50%
		Face to face 50%
C. Health protection specialists, who have an ongoing remit for preparedness and response to events, public health surveillance, and general capacity to review evidence.	A few months	Online 30%
		Face to face 70%
D. Sub-specialists who have dedicated a substantial proportion of their practice in public health to environmental health themes, possibly focused on either pollution, one health, or climate-related issues. May require sub-specialty registration with General Medical Council in environmental public health.	A few years	Online 10%
		Face to face 90%

TABLE 4 Several levels of depth at which the training of health care practitioners may be appropriate.

Audience within health care	Level of training	Mode of training
A. Decision makers in health care would have remit for district-level budget and operational decisions.	A few hours	Online 100%
B. General health practitioner (medical or nurse or physiotherapy or other), may require an overview of the topics and access to appropriate subspecialists, able to chair working groups on specific themes, brief decision makers.	A few days	Online 50%
		Face to face 50%
C. GPs and Pediatricians need to implement a careful attitude in registering data of their patients' health status, occupation, life style, socio economic status, ambient and home environmental conditions.	A few days	Online 50%
		Face to face 50%
D. GPs and Pediatricians who wish to adopt availability to communication with individuals and communities in their professional practice.	A few months	Online 30%
		Face to face 70%
E. Dedicated health practitioners, who have an ongoing remit for providing public support through networking, preparedness, and response to events.	A few months	Online 30%
		Face to face 70%
F. Sub-specialists who have dedicated a substantial proportion of their practice in health care to transforming health care systems toward ecological sustainability.	A few years	Online 10%
		Face to face 90%

TABLE 5 Several levels of depth at which the training of town and country planners may be appropriate.

Audience within town and country planning/architecture	Level of training required	Mode of training
A. Decision makers in town and country planning would have remit for district-level budget and operational decisions.	A few hours	Online 100%
B. General workforce (architects, surveyors, town and country practitioner), may require an overview of the topics and access to appropriate subspecialists, able to chair working groups on specific themes, brief decision makers.	A few days	Online 50%
		Face to face 50%
C. Dedicated workforce, who have an ongoing remit for advocacy, networking, preparedness and response to events.	A few months	Online 30%
		Face to face 70%
D. Sub-specialists who have dedicated a substantial proportion of their practice in town and country planning to transforming communities toward ecological sustainability.	A few years	Online 10%
		Face to face 90%

TABLE 6 Four domains of knowledge required for environmental public health education in climate-related facts.

Level	Learning objectives
Factual knowledge	*Universal basics*: social and environmental determinants of health, psychology of suffering, community response, and behavioral change.
	Climate-related facts: health co-benefits of climate action, sustainability of health factor.
Conceptual knowledge	*Universal foundation*: equity, vulnerability, precautionary principle.
	Climate-related facts: sustainability, "eco-health," planetary boundaries.
Skill-related knowledge	Universal foundation: evidence-based medicine, health education, science communication, collaboration, and system thinking.
	Climate-related facts: clinical diagnosis and management of climate-associated diseases.
Emotional competencies	*Universal foundation:* importance of medical education to society at large, benefits of multidisciplinary collaboration.
	Emotional competencies related to climate-related facts: appreciation of the complicated relationship between equity, sustainability, and health.

Source: Boekels (48) (modified).

2.2 Preparing the future workforce

2.2.1 Overall approach

Based on available frameworks that combine global and local aspects of environmental health (46, 47), curricula already exist for diploma and degree education across all human roles, and there are already numerous examples of environmental health elements having been integrated in such programs (Table 6).

Several barriers to implementation have been identified: (i) lack of knowledgeable teachers of sustainable health systems; (ii) lack of space in the curriculum; (iii) uncertainty of location in the curriculum; (iv) need for learning resources; (v) difficulty in assessing learning; and (vi) emotional impact needing resilience (49). Also drivers and enablers emerge: (i) demand from students; (ii) the move to include sustainability in higher education; (iii) a new legitimacy through mandate of professional bodies; (iv) leadership from other stakeholders; and (v) several sources of support and resources (47).

Having identified best practice from several countries and areas where such initiatives have been conducted, points to the feasibility of rolling these programs to other areas. The scale effect of widespread adoption of such initiatives may spill over beyond the direct awareness of those undertaking such courses and generate sufficient momentum to provide motivation to current decision makers to accelerate the overall trend toward ecological sustainability of human society.

Future success of environmental public health rests on joint action of three groups: (1) public health students; (2) health care students (clinical and other); and (3) other disciplines required for education of all those who should be aware of the implications of their activity on development of ecologically sustainable communities. Recognizing this, educational curricula for diplomas and university qualifications will be required to address needs of such disparate roles. As illustration of such wide range of roles, an example will be given for each the groups.

2.2.2 Public health education

It is common practice that public health practitioners are not training for environmental health topics. For example, in the United States, MPH degrees do not include training in climate change and health issues (50). A combination of competence in specialist disciplines (natural sciences, toxicology, environmental epidemiology, risk assessment, and environmental public health) and general public health skills (management, research, and teaching) was identified in United Kingdom as a requirement of environmental public health education (51). A broad program based on these dimensions, with added inclusion of disciplines relevant to climate and other environmental change, appears as feasible for education of public health students. With focus on climate change, we support a broad six-domain competency framework consisting of (1) climate and environment sciences, (2) drivers of climate change, (3) evidence, projections, and assessments, (4) iterative risk management, (5) mitigation, adaptation and health co-benefits, and (6) collective strategies-harnessing international/regional/local agreements and frameworks (52).

2.2.3 Health care education

Five core domains have been identified by the Global Consortium on Climate and Health Education (GCCHE), with over 300 health professional member institutions from 56 countries: (i) Knowledge and analytic skills; (ii) collaboration and communication; (iii) policy; (iv) public health practice; and (v) clinical practice (53). Three areas have been recognized for learning objectives by the Center of Sustainable Healthcare: (i) Describe how the environment and human health interact at different levels; (ii) Acquire the knowledge and skills needed for more sustainable health care systems; and (iii) Discuss how a physician's duty to protect and maintain human health is affected by the local and global environment (54).

Three areas that deserve attention when developing curricula in this sector are: (i) options for integration of climate change content into existing courses and curricula; (ii) available range of teaching methods such as problem-based learning; and (iii) options for issuing certificates of achievement in the field of environmental health/climate (46).

2.2.4 Education in other disciplines

In almost all of United States universities, climate change was taught in graduate programs (sustainability, urban affairs, geography, and geosciences), but was not cross-listed for the public health program. The implication is that lack of specific training will be detrimental in designing mitigation or adaption approaches for agencies and organizations (50). To create healthy communities, a wider use of accepted science needs to be applied to education of future practitioners in courses (different from health) about climate change and potential strategies for interventions effective to increase resilience of communities.

3 Discussion and suggested approaches

3.1 Discussion

This paper explores the feasibility of providing comprehensive training for environmental public health practitioners and educating students across disciplines to prepare them for addressing the ecological sustainability challenges confronting communities dealing with pollution, biodiversity loss, and climate change, alongside social, economic and health challenges. Our proposal promotes tailored training and education for specific audiences, varying according to their existing roles. While the documented successful experiences impact a relatively small segment of the workforce, it is pragmatic to plan the expansion of existing initiatives to areas currently lacking such training and practices, in different context, geography and disciplinary range.

Examples that we are referring to (Appendix A) including developments in the areas of citizenship, history, technology, and natural sciences curricula have already established a field of education that is highly innovative and valuable for social resilience in the face of current challenges. These curricula instill confidence in applying concepts, skills, and established competencies among professionals from diverse backgrounds, including specialists in public health with expertise in biology, physics, chemistry, sociology, anthropology, nursing, epidemiology, nutrition, or other scientific fields. Despite their efficacy, these experiences encounter limited acknowledgment for registration within legally defined organizations that authorize specialist-level practice, hindering their geographical distribution across countries and continents.

Limitations of our review include the reliance on practitioner perspectives, with minimal reliance on systematic reviews. However, the approaches gathered here cover a wide range of geography, cultures, and practitioner perspectives, and they consistently converge on essential domains. Despite insufficient evaluation of training translation into interventions and public health benefits, identified barriers have been overcome in many cases, providing a foundation for extending these experiences globally. Attention to the registration of trained practitioners in legally recognized roles is crucial, especially outside Europe, as it could form a social infrastructure supporting community resilience within the broad public health economy. Acknowledging differences in capacities and infrastructure across communities and countries, our proposal leverages existing capacities and public health infrastructure globally, using training as a catalyst for strengthening and creating new capacities in environmental public health. Existing international experiences indicate the potential for widespread adoption, emphasizing the transformative impact of developing strong EPH capacity. The overall ambition is that all communities will: first, recognize the value of isolated inter-disciplinary experiences in their midst or elsewhere; second, that such awareness will be extended and translated to acceptability by professional societies in terms of accreditation of such experiences; and third, that any community wishing to initiate their own program for training would be facilitated by networks highlighting available standards and promoting best practice.

We have presented several examples of successful practice in EPH, but many do not include evidence on the persistence of any activity beyond the life of a project or program. Based on the experiences reviewed, competencies required to build integrative practice across professions have been identified and could be further established and promoted. Alongside the ecological sustainability of societies, these proposals need to be sustainable also for the life of practitioners. Those who have undertaken professional training in EPH could be followed up to see if they are employed in these roles, embedded in relevant milieus, for how long and with what impact.

Legal recognition of multi-disciplinary experiences conducted as part of an overall acceptance of a professional qualification has been achieved in some countries (see Appendix), further extension may be facilitated by appreciation that a few months of training embedded within a different disciplinary program makes a substantial difference to the overall competence reached for EPH. The WHO could support this by including EPH as part of their definition of "essential health service."

Also, standards and key performance indicators for professional training could be adapted by professional societies, who could provide a feedback mechanism for practitioners in training to contribute to ongoing review, evaluation and adaptation of training programs.

This review did not differentiate between global and local applications of the proposed EPH practices and how they can be tailored to meet specific needs. We have assembled examples along a range of scopes and themes, and these include many local but also several global applications such as contribution to global UN processes. Some practitioners have noted that achievement in local EPH may be a way to gain confidence and lead to increased validity of proposals for input into global dimensions of EPH.

Research agendas that would contribute to the proposed program would be established ideally in collaborations between innovative multi-disciplinary professional training schools and centers of academic excellence. The motivation to achieve impacts on public health by new synthesis of knowledge and practice would be shared by individuals and institutions promoting such consortia. A key dimension of success of a comprehensive research program would be a balance between (i) space for most innovative interventions such as social prototypes with experimental characteristics, and (ii) promotion of interventions inspired by standards based on replicated effectiveness and supported by competency acquired as part of a training program for practitioners (such as by professional doctorates). Ideally, this balance would be mirrored by a flexibility of professional training programs allowing reaching standard competencies with the widest possible field of application ranging from agroforestry, built environment and social care services.

3.2 Suggested approaches

1. To enhance broader public awareness and education, it is crucial to invest in increasing citizens' literacy regarding the conceptual and practical foundations of environmental public health. This literacy is essential for fostering community resilience.
2. In response to the acknowledged challenges in environmental public health and with the objective of fortifying the EPH functions across society, institutions overseeing the training of professionals and education at both undergraduate and postgraduate levels should consider it imperative to adapt existing curricula and develop new ones. These curricula should encompass comprehensive environmental public health knowledge, hands-on experiences, and the instillation of innovative ideas.
3. To enhance the robustness and significance of current elements within professional training curricula related to environmental change, encompassing topics like climate change, environmental pollution, and biodiversity loss. A key step of the reform initiative should concentrate on sectors already involved in public health matters, including public health practitioners, the healthcare workforce, and other professionals engaged in public health. The innovation we propose would allow that the EPH training activities are based on practice and led by the practitioners as agents for change. A key step will be the acceptance of multi-disciplinary training periods to the point of legal recognition for practice at basic, specialist or sub-specialist level.
4. In parallel, similar reform initiatives to develop, standardize curricula for professionals and practitioners in sectors different from health, with a systematic mapping of the social and health benefit of their activities, are needed by professional societies.
5. National ministries overseeing diverse sectors, such as environment, industry, energy, transport, agriculture, housing, social care, and development, should collaborate with the ministry responsible for higher and professional education, along with related budget-holding agencies. This collaboration may be most valuable when strengthening and enhancing the relevance of curricula for professionals in sectors traditionally distinct from organized public health. This includes individuals like engineers, architects, town and country planners, agronomists, and forestry managers. High-level recognition as suggested above such as WHO considering EPH an "*Essential Health Service*"—and similar recognition by frameworks that inform country/regional allocation for resources such as International Health Regulations (IHR).
6. A particular care must be paid to improve processes for consultation about programs and projects with expected social impacts, by appropriate governance arrangements and communication skills such as listening, speaking, observing and empathizing and also the capability to persuade others on a topic without using force or compulsion while respecting their viewpoints.

4 Conclusion

1. Environmental aspects of health protection and promotion have emerged as crucial public health dimensions over the last 50 years. There is an increasing awareness of the urgency to review and reform education and training. An initial survey of

the range of roles that could be identified as already engaged in environmental public health indicates that a few identifiable groups of students and practitioners could be involved in developing the capacity and capability to contribute to society's resilience in the face of current environmental epochal challenges.

2 There have been valuable ideas and experiences relevant to fundamental education in concepts and awareness of environmental public health practical skills at undergraduate and professional or postgraduate levels.
3 Valuable insights have emerged for postgraduate and professional curricula, benefiting the training of natural scientists, social scientists, health professionals, and epidemiologists already employed in functions of environmental public health within the formal health sector. Harmonizing and disseminating best practices across different countries and continents present several hurdles. Social organization (relation between academia and other organizations), pragmatisms, culture, socioeconomic context will affect how the training is organized and implemented.
4 Insightful ideas and experiences have surfaced regarding postgraduate and professional curricula aimed at training individuals in sectors traditionally distinct from organized public health in environmental public health. These curricula foster confidence in applying concepts, skills, and established competencies among professionals such as engineers, architects, town and country planners (both urban and rural), agronomists, and forestry managers, despite their lack of professional training in public health (also referred to as hygiene).
5 Nonetheless, these experiences encounter limited recognition for registration with legally-defined organizations such as professional and governmental agencies that authorize specialist-level practice, impeding their geographical distribution across diverse countries and continents.
6 Processes for consultation with all stakeholders including representatives of communities affected by such activities and their ecological impacts are often lacking or not implemented. Effective EPH practice depends crucially on inclusive nature of the processes used for designing, promoting, implementing, and evaluating programs and projects whose ecological aspects may affect public health.

Author contributions

GL: Conceptualization, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. AZ: Conceptualization, Formal analysis, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing. MA: Writing – review & editing. CB: Writing – review & editing. HC: Writing – review & editing. RD-D: Writing – review & editing. RE: Conceptualization, Writing – review & editing. NG: Writing – review & editing. OG: Writing – original draft, Writing – review & editing. WH: Writing – review & editing. PJ: Conceptualization, Writing – review & editing. EK: Writing – original draft, Writing – review & editing. PM-O: Writing – review & editing. JP: Writing – original draft, Writing – review & editing. PH: Writing – review & editing. ER: Writing – review & editing. MS: Writing – review & editing. JS: Writing – original draft, Writing – review & editing. CS: Writing – original draft, Writing – review & editing. SV: Writing – original draft, Writing – review & editing. FY: Writing – review & editing. PL: Conceptualization, Formal analysis, Supervision, Writing – original draft, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2024.1373530/full#supplementary-material

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A new environmental public health practice to manage current and future global health challenges through education, training, and capacity building

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Unsustainable globalisation of economic activities, lifestyles and social structures has contributed to environmental degradation, posing major threats to human health at the local and global levels. All these problems including climate change, pollution, and biodiversity loss represent challenges that are unlikely to be met with existing approaches, capabilities and tools. This article acknowledges the need for well-prepared practitioners from many walks of life to contribute to environmental public health (EPH) functions thus strengthening society's capacity and capability to respond effectively and in a timely manner to such complex situations and multiple challenges. It envisions a new EPH practice addressing questions on: Why do this? What needs to be addressed? Who will do it? How can it be implemented? This article focuses on the main challenging EPH issues worldwide and how they could be addressed using a conceptual framework for training. A companion article shows how they have been tackled in practice, providing ideas and experiences.

KEYWORDS
environmental health, public health, ecology, professional training, education, ecological sustainability, environmental change, ecological public health

1 Challenges for environmental public health

Population health problems are complex, as they are determined by environmental, social, economic, and political factors at the local through global levels [e.g., climate crisis (1), obesity (2)]. This requires an integrated and holistic approach for public health science and policy formulation which is also reflected in the WHO social determinants of health framework (3, 4). This paradigm takes into account the distal and structural determinants of health (e.g., economic or employment policies, access to quality housing, healthy food and sustainable transport) as fundamental in determining the unequal distribution of the proximal risk factors (e.g., air pollution, unhealthy diet, sedentary lifestyle, and smoking), and the health status and disease within and across populations (5). Furthermore, policies and actions outside the health sector (e.g., traffic regulations, urban planning and availability of green spaces, obesogenic environment, and food quality) (6) are known to contribute to adverse health outcomes.

The globalisation of economic activities, lifestyles and social structures have contributed to both local and global environmental degradation and change. The collective consequence of the greenhouse gases emissions by individual societies worldwide is perhaps the best-known example of this. At the same time, greater awareness of environmental impacts has been enabled by global linkages, thus resulting in changes at the local (e.g., urban planning) and at the global level (e.g., international agreements), starting with the recognition by the Rio Earth Summit 1992 (6). Several countries have integrated in their legislation the notion of sustainability, the right to health and the right to a healthy environment, and more recently, the UN declared access to a healthy environment a Human Right (7).

The current 'triple planetary crisis' including climate change, environmental pollution, and biodiversity loss, pose major threats to human health both at the local and global level. The impact of these complex challenges is affecting populations worldwide, often unequally distributed with many populations having less or no access to adequate housing, health services, and basic resources such as clean air, water, energy, and healthy foods. These challenges require new approaches and tools in addressing impacts of complex drivers and exposures (8), incorporating concepts such as cumulative impacts of environmental decisions (9), with multiple dimensions from social indicators, living and working conditions, behavioural indicators, or infrastructure such as green space and transport. Environmental Public Health (EPH) (10) is the discipline that addresses and studies such complexity from a multilevel perspective and is increasingly implemented by public health services and environmental protection agencies.

Therefore, the challenge of making a skills transition is urgent, and the poor integration between skills initiatives and the needs of the green transition needs addressing (11).

This article acknowledges the need for well-prepared practitioners from many walks of life to contribute to environmental public health functions thus strengthening society's capacity and capability to respond effectively to such complex situations and multiple challenges. In particular, it will focus on the capacity and capability building required to plan and implement renewed roles for EPH practitioners at local, national, and potentially international levels. The idea for this new role emerged via experiences of multi-disciplinary work beyond the health professions, with practitioners from many sectors including agriculture, town and country planning, engineering, energy, and transport. This type of work often contributed to or accompanied multi-disciplinary interventions (chemical, heat, and flood-related) that supported 'primordial prevention'. The framework for achieving this objective revolves around two interconnected concepts: the 'Common Home', representing the Earth as a shared habitat for all populations, and the 'Common House', symbolising a collaborative space where diverse disciplines come together, from the local level to global.

2 Paradigms for addressing new challenges in EPH

Several frameworks facilitate the task to reinforce EPH services. The Driving force-Pressure-State-Exposure-Effect-Action (DPSEEA) framework approach, initially promoted by WHO, has been further adapted to seek population wellbeing within an ecosystem perspective (e-DPSEEA) (12). The framework allows practitioners to describe, heuristically, a logical conceptual sequence of events that leads to an environmental health problem (13). It is intended to highlight the important links between different aspects of development, environment, and health and to help identify effective policies and actions to control and prevent health effects (14). Adopting this framework requires multi-disciplinarily education and training theories and tools, including knowledge of exposure analysis, environmental epidemiology, and health impact assessment tools.

The Ecological Public Health approach can help address the challenges faced by public health today, by its aims to integrate complexity, multiple interactions and change of societal systems. By doing so, the approach has the ability to understand the ecosystem processes and the system as a whole, and the way it determines population health. Ecological public health provides a framework for considering a holistic approach from public health science to public health actions (10). The ecological approach to public health has been compared to four different conceptual models recognisable in public health: health-environmental, biomedical, behaviouristic-social, and technological-economic. Each of these models has led to successes but has also been characterised by limitations. Both, the successes and limitations have been evaluated in detail elsewhere (15), and within the constraints of the present article one can conclude that the ecological public health model complements and has the potential to integrate other models of public health practice. Prevention services that ignore the conclusions identified in risk assessments at the local community and global level risk being seriously insufficient. Building prevention services based on a shared culture, values and behaviours would make the public health practice work more valid and solid. This is illustrated for example in the case of obesity by recognising that interventions to reduce this problem may be identified more holistically if social and cultural dimensions are considered as deserving to be addressed in themselves alongside physical and biological ones (2).

The 'Health in All Policies' (HiAP) approach, promoted by WHO and adopted by the European Union (EU) in 2006 (16), recommends collaborations through development of intersectoral policy and governance (17). HiAP outlines the adoption of a political overarching vision for a healthier and more sustainable society where all public policy areas can have, directly or indirectly, an impact on health and socioeconomic equity (18). It emphasises the consequences of public policies on health systems, determinants of health and wellbeing, and it enhances the accountability of policymakers for health impacts at all levels of policymaking (19).

However, the ability to respond to such conceptual frameworks for EPH service or the policy recommendations, will be highly dependent on the local context, history, culture, organisational arrangements, capacities and needs, and on who can afford to implement these (20). This recalls the distinction between global and local, as acting within the dimensions of space and time, which is an essential issue for EPH. During the COVID-19 pandemic (21), all the local and global actions, were inextricably linked, being essential to manage the pandemic in many parts of the world.

Currently, there is not an international reference for improving capacity and capability building of EPH functions at national levels. The present form of the WHO-International Health Regulations (22) does not acknowledge environmental factors as determinants of health. Public participation is also an essential force in promoting environmental health quality (23). Supportive policies, regulations, and planning tools would encourage citizens to engage in climate change adaptation and local environmentally friendly planning, and effective and meaningful participation is crucial to ensuring socially just policies (24).

The globalisation of economic activities, social structures, and lifestyle has contributed to both local and global environmental degradation and change. The refore, the role of democracy in pursuing health as the 'common good' (25) may counterbalance the powerful financial and economic pressures on governments. An example is the Erasmus Generation in Europe a term that describes young people who participate in mobility programmes, giving them the opportunity to spend part of their studies abroad, do internships, or work. Through their cultural openness and interconnectedness, they show ability to contribute to building knowledge and the capacity to respond to climate change (26). The EU Erasmus programme contributes to a share of knowledge and understanding, democratisation of accessibility to science and to building a generational capacity for understanding common good. Although a regional only example, the model offers excellent insight on the benefits in lack of boundaries in knowledge transfer and the cultural shift in what community responsibility and response means.

The concept of Planetary Health focuses on analysing and addressing the impacts of human disruptions to Earth's natural systems on human health and all life on Earth (27). Planetary health education across all levels and disciplines will allow transdisciplinary and mutually reinforcing actions to protect and restore planetary health and achieve the Sustainable Development Goals (SDGs) (28).[1]

A simplified set of essential public health functions may be defined based on experience from national public health institutes internationally: (i) preparedness and response; (ii) public health surveillance; (iii) evidence gathering/impact analysis/evaluation of interventions; (iv) effective communication with multiple stakeholders; and (v) advocacy for public health (29). These may be adapted to provide Environmental Public Health (EPH) functions. Table 1 shows how the key EPH functions are mapped and motivated with relevance to each SDG. Some examples of such functions are provided in Reid, 2015 (30) and WHO, 2018 (31). The current status of implementation of these functions varies by country, and so does the role of agencies in delivering them (see section 5). Unless success is built for Goal 13 'CIimate Actions', all the other SDGs will become unattainable (32, 33). Since 2016, the UN has moved from giving highest priority to economic development in a country, to geographic groupings as the highest level of aggregation for SDG statistics (34, 35). This is consistent with the priority advocated in the present paper to consider a country's history and culture (36) as essential context for designing ecologically sustainable communities.

3 The concept of the new EPH practice

3.1 Interdomain partnerships and collaboration

This section introduces a novel environmental public health model for healthcare leaders to comprehend the intricacies of climate change, pollution and Planetary-One Health. Having a deep understanding of the scientific aspects and potential solutions, whilst acknowledging the remaining uncertainties, may be highly beneficial. Health practitioners at various levels have shown it is possible to overcome unique challenges influenced by geography, population vulnerabilities, and socio-economic contexts by evaluating emerging knowledge, from individual health guidance to community-wide adaptation planning. A comprehensive health system response that merges medicine and public health, could help address issues at the intersection of the environment and climate. With the unfolding climate crisis, healthcare professionals are encouraged to take a coordinated, proactive measures encompassing primordial, primary, secondary, and tertiary health prevention (37).

A pivotal experience unfolded in Georgia through a Twinning project, a European Union instrument for institutional cooperation between Public Administrations of EU Member States and of beneficiary or partner countries,[2] involving institutions from Italy, Poland, and the United Kingdom. The project aimed to transfer EU environmental health regulations (38) to the Georgian National Centre for Disease Control (NCDC), focusing on laws, organisational enhancement, and workforce competence. This provided a context for exploration of novel approaches to public health interventions addressing environmental factors for health across a country. A pressing concern emerged: a surge in lead (Pb) poisoning cases across Georgia. Alongside a monitoring programme, preventive measures were deployed and led to a notable reduction in children's blood lead levels. This progress was achieved in

1 Adopted by the General Assembly of the United Nations in 2015, the 17 "Sustainable Development Goals" (SDGs) are the layout to achieve a better and more sustainable world for all by 2030. These goals are a call for action to address a series of global challenges, such as: poverty, inequality, climate, environmental degradation, and justice Essentially for sustainable development to be achieved, it is crucial to harmonise three core elements: economic growth, social inclusion and environmental protection. These elements are interconnected, and all are crucial for the well–being of individuals and societies. From an EPH point of view, all 17 SDGs are different facets of an integrated and systematic approach towards a sustainable and healthy planet.

2 https://neighbourhood-enlargement.ec.europa.eu/funding-and-technical-assistance/twinning_en

TABLE 1 Relationship between sustainable development goals and environmental public health functions.[b]

		Environmental public health function				
Sustainable development goal		Preparedness and response	Environmental public health tracking/ surveillance	Evidence gathering/ impact analysis/ interventions	Effective communication	Advocacy
Goal 1	No poverty		Y	Y	Y	Y
Goal 2	Zero hunger	Y	Y	Y	Y	Y
Goal 3	Good health and well-being	Y	Y	Y	Y	Y
Goal 4	Quality education		Y	Y	Y	Y
Goal 5	Gender equality		Y	Y	Y	Y
Goal 6	Clean water and sanitation	Y	Y	Y	Y	Y
Goal 7	Affordable and clean energy		Y	Y	Y	Y
Goal 8	Decent work and economic growth		Y	Y	Y	Y
Goal 9	Industry, innovation and infrastructure		Y	Y		Y
Goal 10	Reduced inequalities		Y	Y		Y
Goal 11	Sustainable cities and communities		Y	Y		
Goal 12	Responsible consumption and production		Y	Y	Y	Y
Goal 13	Climate action	Y	Y	Y	Y	Y
Goal 14	Life below water		Y	Y	Y	
Goal 15	Life on land		Y	Y	Y	
Goal 16	Peace, justice and strong institutions		Y	Y	Y	Y
Goal 17	Partnerships for the Goals		Y	Y		Y

Note: Y= "Yes, a relationship between a SDG goal and an EPH function may be recognised." [b]Preparedness and response: Preparedness—making arrangements, creating and testing plans, training, educating and sharing information to prepare communities should an emergency eventuate. These are also ACTIONS and they are happening all the time. Response—the assistance and intervention during or immediately after an emergency. (https://resilience.acoss.org.au/the-six-steps/leading-resilience/emergency-management-prevention-preparedness-response-recovery). Environmental public health tracking/surveillance: systematic, ongoing collection and analysis of information related to disease and environment, and its dissemination to individuals and institutions. (See Annex). Evidence gathering /impact analysis/interventions: are designed to unearth the 'unexpected' negative effects of a change on an organisation. It provides a structured approach for looking at a proposed change, so that you can identify as many of the negative impacts or consequences of the change as possible (https://www.mindtools.com/axt4kh3/impact-analysis). Effective communication: is a process of exchanging ideas, thoughts, knowledge and information such that the purpose or intention is fulfilled in the best possible manner. In simple words, it is nothing but the presentation of views by the sender in a way best understood by the receiver (https://theinvestorsbook.com/effective-communication.html). Advocacy: activities related to ensuring access to care, navigating the system, mobilising resources, addressing health inequities, influencing health policy and creating system change are known as health advocacy. (https://pubmed.ncbi.nlm.nih.gov/27866451/#:~:text=In%20the%20medical%20profession%2C%20activities,are%20known%20as%20health%20advocacy).

a multi-disciplinary collaboration including health care practitioners, epidemiologists, and natural scientists across existing institutional divisions, and indicates the feasibility of co-ordinated effort to face a novel environmental challenge (39).

3.2 What is the new EPH practice?

An approach for identifying essential competencies in public health is extended to pinpoint valued skills and competencies by current employers (40).

The new competencies for EPH may be applied to the 'three domains' of existing public health practice, described in terms of three interrelated but distinct dimensions: (1) health promotion, which draws heavily on the local government roots of the profession, socioeconomic influences and health promotion, and tackling the underlying determinants of health; (2) health protection, which incorporates communicable disease control; environmental, chemical, radiation and nuclear threats; and occupational health; (3) health service quality improvement, which incorporates healthcare systems, service quality, evidence-based practice, clinical effectiveness and health economics (41). This provides a robust operational framework that includes the areas of practice, the services to be delivered, and the roles and responsibilities of those delivering them. This is particularly important in describing the core skills, knowledge, and competencies needed so that the respective workforce can carry out their respective roles. As such, this framework has the potential for adaptation to underpin educational and training provisions (42).

The overlap of the three domains of public health practice also helps inform the development of education and training addressing planetary health from the perspective of environmental public health service. In this context, skills and competencies related to dealing with health impacts of the climate crisis are integrated in the curriculum of public health schools and are now a required competency for a health practitioner in some locations (43).

The skills mentioned apply to the advancement of public health across all fields, extending beyond healthcare services. This approach is justified as healthcare systems are responsible, as estimated previously, for approximately 4% of global greenhouse gas emissions. Thus, broad societal changes, and not purely clinical health care of individuals, are required to safeguard public health. There is a growing call for closer collaboration between clinical medicine and public health. The COVID-19 crisis underscored the pivotal role of primary and community healthcare (P&CHC) in both short-term and long-term healthcare. It highlighted the necessity for P&CHC to collaborate in contact tracing efforts, aligning with various healthcare organisations including local and national public health institutions, as well as community-level groups and health workers.

3.3 Scoping the tiers/levels of the new EPH practice

Recognising the central role of the development of social change towards sustainability (44), the role of public health education and training is essential. The public health workforce can be defined as 'a diverse workforce whose main responsibility is the provision of the main health activities for the public, regardless of their organisational basis', emphasising the broad and diverse nature of public health. Public health increasingly includes the role of the 'wider' workforce: people who are indirectly involved in activities but whose work can contribute to improving population health (45).

Practitioners of that broader public health can be divided into three groups: (1) public health specialists; (2) people indirectly involved in public health activities through their work; and (3) people who should be aware of the implications for public health in their professional life (46). To this end, practitioners of all three groups require knowledge and skills in similar fields but on a different level. This holds for general public health, and similar considerations can be made first and foremost for environmental public health (EPH). The evaluation of which disciplines and knowledge are relevant to forming a category of professionals could be conducted by scientific societies and professionals to whom this task was relegated by the State or other parts of civil society (47).

Practitioners in each of these group share the same mission to develop capacity towards achievement of the SDGs as outlined in section 1.3, and according to the roles outlined in section 5. The proposal for this role is considered within the context of community, history, culture, economic and social dimensions. The practitioner originates from the community and works across the disciplines, knowledge and resources available. The proposal, based on experiences from many communities, also offers integration of knowledge beyond the community boundaries, for regional and global sharing of such experiences. Also, the values of justice, culture, and relationships highlighted by consensus statements of Indigenous communities on the theme of planetary health are best served by choice of governance that are inclusive of representatives of indigenous communities proposing their specific perspectives, methods, and topics (36, 48). This is expected to benefit all communities and individuals within them, as it communicates that the key step towards ecological sustainability is not the provision of a new institutional service, but the recognition of the value, wealth, and health already present in each community and individual, and that can be re-oriented to take a new course when faced with challenges related to climate change. In any case, stakeholder engagement needs to consider those affected by climate and environmental change and set out a clear strategy for communication and engagement, ideally extending to a role in the design and monitoring of any research or intervention.

3.4 How and why does the public health practitioner advocate and assume custodianship?

Health status is a synthesis or 'super-indicator' of the social impact of multiple influences from all sectors of human decision and activity. Therefore, health integrates all other activities (49). Indicators are key to awareness of changes in health status in time and space, and to inform activities to take custody of public health by interventions addressing preventable factors.

Acceptance of the value of health information as a series of indicators of relevance for decisions beyond the health sector is key to the development of ecologically sustainable communities.

In the context of addressing the climate crisis, practical initiatives exemplified by the efforts of *Santé Publique France* and the International Association of National Public Health Institutes (IANPHI) highlight the use of health as a catalyst for action (50). Recent discussions within WHO Europe underscore the pressing challenge posed by the 'triple crisis', arising from the interconnected issues of climate change, environmental pollution, and biodiversity loss (51).

Within this framework, a public health practitioner actively engaged in EPH, whether within the healthcare sector or other sectors, can play a crucial role in spearheading the development, design, analysis, and evaluation of systems aimed at incorporating ecological sustainability into various programmes and projects. The EPH practitioner may assume diverse roles, from advocating and motivating cross-sectoral collaborative efforts to challenging the status quo. Communication with those impacted by environmental issues is key as part of consultation and possible collaboration with agencies and groups responsible or affected. Such a role might initially be met with resistance, but it has the potential to prompt alternative, environmentally resilient infrastructure and service solutions.

Simultaneously, any healthcare practitioner, including those in clinical and social care settings unrelated to prevention services, can act as an advocate for the inclusion of health and social assessments in infrastructure and service planning. When such plans are positioned as steps towards sustainability, the consideration of health, well-being, and social impacts offers a tangible contribution to intervention selection, complementing the customary technical and financial criteria mandated by law and tradition.

4 How does the new environmental public health practice operate?

4.1 Practising environmental public health within the health work force

4.1.1 EPH as a public health task

First, a few assumptions are made regarding public health:

1 Protection and promotion of healthy lives in their social, economic, and environmental context.
2 The overall approach is analytical and systemic at the same time, i.e., observing reality from two different but complementary perspectives: the analytical (reductionist) perspective and the systemic one (since the problems are all interconnected and interdependent), each of which makes use of a broad heritage of methods, knowledge and skills.
3 An interdisciplinarity and cooperative approach is required. Specialisation always must follow the integration of knowledge and cooperation between the parties, so that exaggerated attention to detail does not produce deleterious effects on the general economy of the system. To be successful, therefore, it is necessary to develop one's professional profile but also to share knowledge, learn from each other and channel creativity towards cooperation and the realisation of common and shared objectives.

The public health workforce encompasses a diverse collective responsible for executing essential public health tasks, irrespective of their institutional affiliations. These workforce members fall into three primary categories (as outlined in section 4.3) and require varied levels of knowledge and skills in related areas. This principle holds true for public health in general and must be transferred to environmental public health. The determination of the relevant disciplines and expertise needed to categorise professionals can be delegated to scientific and professional societies, either by the State or other civil society segments.

For example, the Netherlands, at the request of several ministries, created a category of environmental health specialists characterised as public health physicians with additional training in toxicology, environmental sciences and epidemiology (52). In England, the Faculty of Public Health, comprised of specialised public health professionals, including physicians and other experts, established the necessary competencies in environmental public health (52, 53). Besides general organisational competencies in research, teaching, and service management, five areas of specialised expertise are identified for public health practitioners in this field (54): toxicology, natural sciences, environmental epidemiology, risk assessment, and environmental public health.

4.1.2 EPH as a task for clinical health care workers

Second, EPH has a role within clinical health care professionals. Healthcare primarily concentrates on diagnosis and treatment. Practical knowledge, gained from everyday hands-on experiences, complements procedural knowledge, which deals with how to perform specific tasks in clinical, public, environmental health, or management. Health professionals can drive social and policy change (55) as they are generally highly trusted (56) and have influence at all levels of society. With trust comes the responsibility to influence wisely and lead effectively, which requires collaborative engagement beyond individual actions (47), thus 'Health professionals will be called on to engage as humble, informed, and trusted partners in the collective, boundary-crossing effort of transforming practises and structures to better sustain the health and wellbeing of all life, including our own' (57).

Training of professionals in sustainable development and the green economy with a focus on public health management and risk assessment would be beneficial to protection and promotion of healthy lives by prevention of causes of ill-health. They should also be familiar with urban health and pollution-related issues to address various diseases and ensure healthier urban environments (58).

4.1.3 EPH as a task for practitioners in many disciplines

Third, EPH covers contributions from both public health and clinical health care (15). Typically, clinical and public health knowledge often do not integrate knowledge on the health determinants related to environmental health, which include population impacts of pollution, biodiversity loss or climate change—therefore defining boundaries between the two services (59). It is encouraged for medical and health knowledge to recognise one identical set of values and criteria with prevention as an essential focus for clinicians, healthcare practitioners, and public health professionals (60).

Public health services worldwide are increasingly fostering interventions that aim to protect and promote health and the environment (61) as described in Table 2.

There is growing recognition that health care professionals require further training about EPH. The Association for Medical Education in Europe for example, emphasises the importance of equipping health professionals with the knowledge, skills, and values that promote sustainable health, and advocate for environmental and social change whilst protecting the planet (47).

Health care professionals are encouraged to engage with environmental concerns both in their role as clinicians, environmental and public health practitioners, regardless of the national organisation. This applies to undergraduate students, as declared by teachers (63, 64) and students eager to stimulate their institutions in this direction (65). It is also relevant to clinicians in training and those already practising, particularly those defined as Family Doctors (FDs) (21) and Family Paediatricians (FPs) (66). EPH training of physicians (as well as for non-physicians, see below) should include knowledge and skills in recognising, diagnosing and treating health problems caused by environmental risk factors (ERFs) (see Table 3).

4.2 Practising environmental public health outside of the health work force

Environmental health, environmental public health and prevention are matters that involve many disciplines and competencies.

Over 70 professional categories relevant to environmental health in Europe were identified in a review published in 1998, including

TABLE 2 Public health services.

Services of health protection
- Supply of potable water
- Control and safe use of foods and medicines
- Control of air quality
- Proper disposal of wastes
- Fluoridation and oral hygiene
- Control of radiation and toxic agents
- Occupational safety
- Injury prevention
- Surveillance and control of infectious diseases
- Urban planning
Individualised services for health promotion
- Encourage physical activity and exercise
- Encourage proper nutrition
- Encourage personal and household hygiene
- Encourage respect for others
Collective services of health promotion
- Advocacy and public policies
- Control the use of tobacco, alcohol and other drugs
- Providing decent and sanitary housing
- Standards for urban development
- Green zones
- Walkways and pedestrian zones
- Bikeways
- Development of social capital
- The organisation of the community
- Civic culture—Respect
- The organisation of the community
Preventive medical services
- Family planning
- Control of pregnancy, childbirth and puerperium
- Growth and development
- Immunizations
- Prevention of teen pregnancies
- Screening and monitoring of cases

Source: Echeverry (62), modified.

academics, medical specialists, environmental scientists (e.g., epidemiologists, natural scientists, social scientists and experts in occupational hygiene) and professionals (such as environmental health workers, technicians, and architects) (67). Yet, few of these professions have increased their involvement in environmental health and prevention in the past two decades. Prevention requires a continuous updating of knowledge in multiple disciplines to be translated into actions to protect and promote health. That knowledge concerns particularly the environmental factors (Table 3).

Close collaboration between a wide range of thematic areas and scientific disciplines may be helpful given the great diversity of professional categories involved in prevention in general and environmental health in particular. There also is a clear need for intersectoral collaboration, as recognised by the WHO with the 'Health in All Policies' approach (68). In practice, a limited number of agencies and groups may be required for any specific project or programme, and consultation with scientific and professional societies may allow to identify appropriate individuals.

TABLE 3 Fields of knowledge relevant to disease prevention, with particular attention to key areas for environmental health.

Prevention and control of injuries	• Predictive modelling of injury scenarios • Contingency and logistics management • Perception of injuries and psychology • Economics of injuries and risk
Water quality	• Water and wastewater chemistry • Applied hydrology • Hydrogeology • Marine science • Hydromechanics • Technologies for water supply and water treatment • Agriculture, industry and energy management
Air quality	• Climatology • Industrial management and energy production • Meteorology • Atmospheric chemistry • Pollutants behaviour • Atmospheric and climatological modelling • Monitoring and modelling
Food quality and safety	• Economics of agricultural management • Veterinary Sciences • Soil Sciences • Food production technology • Risk analysis systems • Food health promotion • Biotechnologies and genetic modification technologies
Waste management and soil pollution	• Solid and liquid waste management • Soil science • Management and rehabilitation of contaminated land • Waste prevention management
Human ecology and housing	• Building management • Housing conception and use • Territory planning • Rural management • Architecture • Urban planning • Construction and housing sciences
Worker's health	• Ergonomics • Job security • Environmental Protection • Engineering technology • Work hygiene • Bioengineering technology
Energy	• Modelling and forecasting energy consumption • Long-distance monitoring and remote sensing techniques • Geographic information systems • Energy transport • Energy production and consumption
Transport management	• Economics of transport and logistics • Transport modelling • Engine engineering • Behavioural studies on transport • Road safety studies

(Continued)

TABLE 3 (Continued)

Land use planning	• Urban and rural development plans • Management of open spaces • Nature conservation and wildlife protection • Management of the contaminated territory • Agricultural management • Management of natural resources and energy
Agriculture and fish production	• Plant and crop science • Animal husbandry • Veterinary science • Chemical and pesticide safety • Marine and fisheries sciences • One Health approach
Ionising and non-ionising radiation	• Techniques for monitoring and radiation protection of the natural background • Safety audit of nuclear power plants • Management of nuclear waste • Radiation monitoring • Predictive modelling techniques • Remediation techniques for contaminated sites • Epidemiological techniques applied to the study of exposure to non-ionising radiation sources
Noise control	• Noise exposure assessment techniques • Study of noise-induced disturbance • Community-wide noise assessment
Tourism and recreation	• Bathing water quality • Control of recreational facilities • Applied ecology • Littoral and estuarine sciences
Control of disease vectors	• Entomology • Parasitology • Applied zoology • Infectious disease control techniques • One Health approach

Source: Leonardi et al. (15).

Attention must also be paid to those working in environmental management/sustainability professions to enhance their knowledge of health/PH/EPH—focusing on the health impacts of their efforts, to align to the EPH goals (57).

4.3 How do these roles integrate, collaborate, and co-function?

The overarching objective of this approach is to realise the full health potential for all individuals, with a dual focus: firstly, to promote and safeguard health within the context of the environment and life transitions, and secondly, to curtail the prevalence of major diseases and injuries whilst mitigating their associated suffering.

Its ethical foundation rests on three fundamental dimensions and principles:

1 Healthy Environment as a Fundamental Human Right: Recognising access to a healthy environment as an inherent human right (7).
2 Equity in Health and Solidarity: Emphasising health equity and collective responsibility (69).
3 Participation and Responsibility: Promoting active involvement and shared responsibility in health development (70, 71).

Despite the extensive promotion of action strategies grounded in scientific, economic, social, and political sustainability, their full implementation remains unrealized.

The earliest codification of intersectoral action is exemplified in Harris et al. (72), where elements of the health sector and other sectors, including environment, transportation, energy, urban planning, and social care, collaboratively address health issues to achieve more effective, efficient, and sustainable outcomes. Such intersectoral action necessitates involvement of policy authorities and national and local practitioners, being multidisciplinary, transdisciplinary, and inclusive of various agencies and stakeholders. It is an ongoing dynamic process.

The importance of improving the relationship between public and private research and science was confirmed in a WHO conference (73).

Preventive services are encouraged to integrate scientific advancements through collaborations with entities such as civil protection and public health institutions. To enhance prevention services, individuals from diverse educational backgrounds may participate, with training programmes blending scientific and professional competencies. This can be achieved through curriculum development, integration, and cross-institutional training experiences. Training duration may vary to accommodate different needs, ranging from a few days for structural managers to three to 6 months for specialisation in fields like medicine or public health. Integration into specialisation programmes is a viable approach when mutual recognition of segments of professional training can be agreed between those responsible in different scientific and professional societies.

Regarding the economic feasibility of these proposals, there are three aspects: (1) costs to individual practitioners undertaking the training; (2) costs to employers and professional societies currently responsible for funding training programmes; (3) costs of implementing ecologically sustainable options for human activity when such options emerge from the work of practitioners and cost more than the alternative. There is a close relation between these aspects, so that addressing one will facilitate addressing the others. For example, if an employer provides a position with a clear role in EPH, the employer would bear the cost and then the individual could shape their own training whilst employed, making it viable for their own personal career. Decision analysis has aided the reallocation of funding to public health objectives in the case of health services, and in principle such methods could be applied to activities that produce climate and other environmental change with a known effect on health.

4.4 Leadership and governance

The scope of EPH across health and non-health sectors indicates that a single source of leadership is not realistic or fruitful. Leadership and governance in this enterprise are inspired by the concept of the conductor and the orchestra. Sharing of fundamental values underlying movement towards ecological sustainability represents the surest foundation for several 'orchestras and conductors' to work in harmony. Accordingly, governance, which refers to the tangible framework and operational activities, facilitates the implementation of EPH through collaborative efforts across multiple sectors (transdisciplinary) requiring intersectoral collaborations. For example, when nature-based solutions in agroforestry are implemented with a view to improve planetary health and human health as part of that, it was appropriate for agronomy and forestry specialists to assume leadership (74). Conversely, when an effort was made to characterise the impacts on health and sustainability of alternative choices in pollution-generating activities in urban areas, the leadership was taken by specialists in engineering with input of natural scientists and public health professionals (75).

4.4.1 Role of policy makers

Policy makers can facilitate development and application of promising new approaches, in particular when they permit experimentation in key sectors of the economy at least in a few dedicated geographic areas, to support design and testing of bold proof of concept activities. This would provide an element of dynamic exploration and selection of the most effective solutions alongside policies to support system-wide changes, such as re-design of building codes and agroforestry practises towards ecological sustainability, or introduction of a national skilling wage. Modes of inclusion and dialogue between agencies responsible and groups impacted responsible for or promoting alternative solutions may be reviewed regularly as part of governance arrangements. In any case, a policy framework that can support the new EPH practices would rest on cross-ministry coordination, to clarify that a ministry or department responsible for production of emissions or pollution has a responsibility for EPH alongside the Ministry of Health and the Ministry of Education. This could be as simple as a cross-departmental group with this function or be an element of an integrated technical agency such as in the case of the RIVM in the Netherlands, a multidisciplinary agency funded by four different ministries.

4.4.2 Role of public health practitioners

Health practitioners can play a role in creating sustainable communities by integrating health and social well-being data into decision-making across various sectors. To provide valuable health information for decision-makers outside the health sector, EPH functions are crucial. It may be beneficial for EPH to be led by experts experienced in considering population-wide health effects within specific cultural and historical contexts. They may be invited to act as 'conductors' of EPH, offering feedback to decision-makers in other sectors in a transparent manner. This transparency fosters consensus on recommended interventions. For instance, Turin engaged local communities in siting waste treatment facilities through a 'deliberative democracy process'. Protection within the public health economy is necessary for sustained employment and independence from healthcare sector reforms (76).

This can also refer back to ethics. If intersectoral inclusiveness in informing EPH practice, ethics and legal agreements (or mandates) can be the mechanisms to ensure a running infrastructure.

4.4.3 Obstacles and ways to address them

Obstacles and objections that can be expected in this area are recognised, and concern cultural/disciplinary and institutional barriers, academic competition, and economic/financial resources. The experiences conducted so far highlight the value of moving from agreements in principle to the role of practical arrangements, such as joint supervision by staff in separate organisations of projects by practitioners, secondments with tasks according to a previously agreed joint agenda, professional doctorates where the student is embedded in an organisation where their development of new knowledge is co-designed by business supervisors alongside researchers in academia, and immediately used in the business operations. Such arrangements would support individual career progression whilst also facilitating development of new institutional and inter-agency functions and capacity. The latter would be enhanced by active recognition of the macro-areas or settings, such as school, hospital, shipyard, food production facility as well as the broad function such as data collation, development of guidelines, safety protocol implementation, comparison with operation in similar districts, communication and prevention services. Any specific activity would need to consider a specific setting and function and may benefit from awareness of its implications for environmental public health. Overall, the experiences reviewed confirm that in many cases detailed actionable steps to implementation may be identified that allow institutional and economic barriers as well as academic competition to be overcome, rendering the activity feasible.

In sum, these arrangements would enable any output from EPH to be co-designed and delivered effectively to decision makers and those who advocate certain interventions or courses of action. It would be the responsibility of these non-health sector roles to reflect, question, amplify the conclusions and recommendation with explicit processes that would be specific to each sector.

4.5 What should the new practitioner look like?

Various professionals from public and private sectors (health, environment, architecture, etc.) have been identified to contribute to ecologically sustainable health and well-being. Each profession may need to review the design of the competencies of the new Environmental Public Health Practitioner. These practitioners will operate at different levels, from early career to decision-makers. The research component of their professional profile will vary depending on whether they work in academic or service/professional settings in which research is conducted. A European Commission-funded project (DG SANTE) established a network for environmental public health specialist training (77). This initiative identified various approaches within European countries regarding profiles, university courses, training, and registration requirements for health specialists in environmental expertise. Similar efforts exist in other continents. Common elements include the importance of social and natural sciences, epidemiology, and toxicology as foundational knowledge for environmental public health specialists (52, 54). A similar approach could be applied to biologists, geologists, sociologists, architects, and other disciplines involved in environmental public health. Considering the importance of different contexts (e.g. historic, religious, cultural) that affect all sectors of human decision making, the practitioner may benefit from referring to this context when declaring the values underlying the design, analysis, and interpretation of any EPH task. Statements are available from a variety of cultural and religious leaders (78).

It is important for public health agencies to strengthen the visibility and legitimacy of Community-Based Participatory Research (CBPR) approach. This approach will help to enhance the credibility of public health practitioners and improve the preparedness activities of public health boards (79). As mentioned earlier, this approach must be based on a clear and authoritative scientific basis.

To address the needs of such varied collection of practitioners and their interaction and co-operation, a few examples of training scenarios are provided below:

4.5.1 Training integration amongst family medicine practitioners and prevention bodies

An example of training experience in another speciality is clinicians' experience in preventive services. If a General Practitioner (GP) in training can attend an internship in the specialisation course in Public Health on topics that are part of the training curriculum (for example, organisation, epidemiology, health promotion…), this would allow the student to know the purposes, methods and possibilities of integration with GPs activity.

This training exchange is to be seen as a training enrichment both for individual practitioners and the departments they are attending. The positive result is the training of practitioners to be better able to develop and operate in inter-agency collaborations.

4.5.2 Training integration amongst researchers—prevention officials

An integrated training approach involves exchanges between research institutes, especially epidemiological ones, and specialists in hygiene and preventive medicine. This approach should also include young researchers from various disciplines gaining experience in prevention services. These exchanges allow research and public service institutions to benefit from each other's expertise and contribute to different projects, promoting mutual learning.

4.5.3 Training integration amongst environmental protection agencies and prevention facilities staff

If such a model could be fruitful for primary prevention in general, it might be even more in the case of environmental prevention. The agencies could 'exchange' trainees in the health sector and sectors other than health. In this case, the benefits could be even more significant. It would be a training experience for public health specialists in epidemiology services or Environmental Protection Agencies (EPAs) and, vice versa, by EPA workers with degrees in physics, chemistry, geography, environmental science or other disciplines employed as environmental specialists in an epidemiological research institute or an epidemiology or environmental prevention service, or in a public health laboratory, or food hygiene service, or a veterinary service of a health agency.

The examples provided clearly show that working together leads to familiarity with laws and methods relevant to the professional practice of colleagues active on shared objectives. This familiarity will also take place on a practical level. Hearing a worker on the phone whose context is understood creates the best conditions for creating an effective network aimed at prevention.

4.5.4 From training to practice

In general, the training of officials or consultants with experience in different agencies facilitates the implementation of multi-disciplinary interventions with the skills of various agencies. This integration depends on the awareness that the objectives are achievable only if activities requiring complementary skills are shared.

However, it may be fruitful to arrange accreditation of some roles in environmental public health supported by some legal statements, which recognise that training is linked to a specific integrated training path, which is necessary for the achievement of the speciality, for registration in a professional register and the practice of a legally recognised role in public health.

In addition to training specialists with multi-disciplinary sensitivity and direct knowledge of practitioners 'in the other field', it also is advisable to consider a training course of the prevention worker's career. Placement in other sectors in the post-speciality years or the preparatory phase to managerial positions in public health services or EPAs is essential to achieve multi-disciplinary and inter-institutional communication skills.

Such knowledge sharing might be helpful also to raise awareness of steps needed for sustainable development and to reduce the environmental footprint of health services.

5 EPH organisational synergies for education and training

There is a traditional distinction between 'education', the development of fundamental cultural and scientific knowledge, and 'training', referred to concepts, skills and competencies that constitute the ability to apply knowledge to reality as part of professional or practical roles in society. The tasks of providing education and training even though closely related, are distinct and have several differences; a key one is that training is focused chiefly to 'practitioners', people who are already employed and who would like to develop their role, whereas education is mainly focused on 'students' who may or may not go on to be professionally involved in applying their knowledge.

The following comments and proposals are addressed to different targets with different objectives, addressing various challenges and modes of action.

The WHO is developing different sets of environmental health tools and training materials for health professionals, such as the air pollution and health training toolkit. A mapping of other air pollution and health training opportunities has also been published (80), presenting courses from different geographical regions whilst providing some good practices for creating new training programmes. WHO has developed various products to educate healthcare professionals on climate change, children's health, environmental risk factors, and more. They have developed a comprehensive collection of WHO and UN guidance for creating healthier environments, consisting of 500 actions and interventions. This resource is valuable for decision-makers including mayors, public health officers, and ministry staff involved in health and environmental matters (81).

The World Organisation of National Colleges, Academies and Academic Associations of General Practitioners/Family Physicians, the World Organisation of Family Doctors (WONCA), and Environment and Telessaúderes-UFRGS launched the Planetary Health course for Primary Care. With a focus on clinical practice and the reality of health professionals, the course is designed to introduce family doctors and other primary health care professionals and students to planetary health; and to inspire and guide them to educate others or become advocates in various ways (82, 83).

The Global Consortium on Climate and Health Education (GCCHE) was created at Columbia University in 2017. With the aim to develop core competencies for climate and health education and equip healthcare professionals worldwide with the knowledge and skills to address climate-related health challenges, it has an input from over 300 member schools across 50+ countries. They are central to the Climate Change and Public Health Toolkit by the Association of Schools and Programmes of Public Health (84, 85).

As per the Statement of Planetary Health Principles (87), as detailed in Annex, the *in vivo* Planetary Health group affiliated with the Worldwide Universities Network (WUN) contemplates the following:

> 'Advocacy: We should actively promote the increased integration of a planetary health perspective into the education of healthcare professionals. Additionally, we should advocate for early-life education in scientific disciplines that serve two critical purposes: first, to demonstrate the intricate interconnectedness of human life with Earth's biodiversity and natural systems; and second, to illustrate how individual well-being is intricately linked to our coexistence with fellow humans and other life forms'.

Such discourse is encouraged in the education of caring and teaching professionals (and widely throughout society). Individuals will strive to lead by example, reduce primacy, and encourage unity.

6 Conclusion

To support conversion of human societies to ecological sustainability before climate and other environmental change produce impacts that threaten the resilience of social fabric catastrophically, it is important to empower practitioners of all disciplines relevant to environmental public health. Supporting the education of future generations to move in this direction, as well as the current generation of decision makers, can help ensure justifications and plans for the more sustainable options within the available spectrum of the workforce making use of their current roles.

Training and enabling practitioners in multiple disciplines for the EPH task is highly encouraged. Practitioners of health and other disciplines may play a role within consortia directed at the overall goal of practical re-orientation of activities with human health impacts and related decision making.

This paper provides a reflection on the overall path of environmental health prevention training and education, focusing on conceptual frameworks of reference that can inform the overall perspective for implementing environmental public health on the ground. A companion paper (86) summarises some experiences and proposals from around the world. These confirm that the call has already been heard and produced several results in the real world; hence, the companion paper presents recommendations for those who arrange training activities in this field. The main point that has been raised is the need for and feasibility of integration, and re-orientation of current practice by on-the-job training inspired by experiences already completed, as well as influence of future practice by re-directed educational frameworks.

Author contributions

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Annex

Glossary

Capacity-building: the capacity of individuals and groups to solve problems requires more than training—it also requires networks, supports, and infrastructure. Thus the term encompasses much more than 'training' to include team-building, communication skills, and networks (88).

Competence/Skill: 'competencies' and 'skills' are not interchangeable terms. Competencies integrate knowledge, skills, values, and attitudes for effective performance. Skills, on the other hand, are specific abilities that lead to predetermined results in a particular setting, categorised as technical or interpersonal. ('soft' skills) (89).

Community Health: is a major field of study within the medical and clinical sciences which focuses on the maintenance, protection, and improvement of the health status of population groups and communities (90). The WHO defines community health as environmental, social, and economic resources to sustain emotional and physical wellbeing amongst people in ways that advance their aspirations and satisfy their needs in their unique environment (91).

Eco-health: is a field of research, education, and practice that adopts systems approaches to promote the health of people, animals, and ecosystems in the context of social and ecological interactions (92).

Ecological public health: focuses on interactions, with one strand focusing on the biological world—in concerns about increasing strains on biodiversity or antimicrobial resistance, for example. Another strand centres on material issues such as links between industrial pollution, energy use and toxicity, and the impact on human species and nature. The advantage of ecological thinking is that it theorises complexity, a key feature facing modern conceptions of health (93).

Ecosystem health: Not to be confused with Ecological health or Environmental health Ecosystem health is a metaphor used to describe the condition of an ecosystem. This term is often used in portraying the state of ecosystems worldwide and in conservation and management. For example, scientific journals and the UN often use the terms planetary and ecosystem health, such as the recent journal The Lancet Planetary Health (94).

Environmental health: Clean air, stable climate, adequate water, sanitation and hygiene, safe use of chemicals, protection from radiation, healthy and safe workplaces, sound agricultural practices, health-supportive cities and built environments, and a preserved nature are all prerequisites for good health (95).

Environmental Justice: is the fair treatment and meaningful involvement of all people regardless of race, colour, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies (96).

Environmental Public Health: can be defined as 'The science and art of preventing disease, prolonging life, and promoting health, where environmental risks are an important factor, through the organised efforts of society' (97). It addresses aspects of health that are determined by interactions with the environment and occurs on many scales: genetic, cellular, individual, family, community, regional, national, and global (99).

Environmental public health tracking/surveillance: systematic, ongoing collection and analysis of information related to disease and environment, and its dissemination to individuals and institutions (99).

Global Health: The 'global in global health has in practice referred to the reach of a small set of non-state actors—non-governmental organisations, pharmaceutical companies, philanthropies and universities—capable of defining new health agendas for the planet. The peculiar epistemology of global health emerged in the post-Cold War period from the widely shared belief that the transnational nature of contemporary threats to health—the propagation of infections through air travel, or the rise of chronic diseases associated with trade liberalisation and multinational corporations—could not be addressed through the old international health system, built around nation-states, but required new global solutions able to work across political and geographical borders (100).

Health Equity: Equity is the absence of unfair, avoidable or remediable differences among groups of people, whether those groups are defined socially, economically, demographically, or geographically or by other dimensions of inequality (e.g. sex, gender, ethnicity, disability, or sexual orientation). Health is a fundamental human right. Health equity is achieved when everyone can attain their full potential for health and well-being. (https://www.who.int/health-topics/health-equity#tab=tab_1).

Health Inequalities: are unfair and avoidable differences in health across the population, and between different groups within society. (https://www.england.nhs.uk/about/equality/equality-hub/national-healthcare-inequalities-improvement-programme/what-are-healthcare-inequalities/).

One Health: is an integrated, unifying approach that aims to sustainably balance and optimise the health of people, animals and ecosystems. It recognises the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent. The approach mobilises multiple sectors, disciplines and communities at varying levels of society to work together to foster wellbeing and tackle threats to health and ecosystems whilst addressing the collective need for clean water, energy and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development (101).

Planetary health: The definition published by The Lancet: 'the achievement of the highest attainable standard of health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social -that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish. Simply put, planetary health is the health of human civilisation and the state of the natural systems on which it depends' (102). Planetary health is the interdependence of all ecosystems, natural and human-made, promoting health equity and wellness. It requires integrated approaches, breaking down conventional boundaries to foster science and cultural collaborations (87).

Primary health care: is a whole-of-society approach to health and wellbeing centred on the needs and preferences of individuals, families and communities. It addresses the broader determinants of health and focuses on the comprehensive and interrelated aspects of physical, mental and social health and wellbeing. It provides whole-person care for health needs throughout the lifespan, not just for a set of specific diseases. Primary health care ensures people receive comprehensive care—ranging from promotion and prevention to treatment, rehabilitation and palliative care—as close as feasible to people's everyday environment (103).

Primary and Community health care: could play in managing health emergencies, addressing key environmental and social aspects, and assisting in designing the interventions to control them. P&CHC is important locally and globally. Societies are ageing, health spending is rising, and it is imperative to redesign health systems that contribute to community health by addressing environmental factors (21).

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Grand (meta) challenges in planetary health: environmental, social, and cognitive

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The term “planetary health”, coined in the 1970s, arose from planetary consciousness, stimulated in part by the dawn of the space age, and commensurate recognition that our species faces extraordinary obstacles (“limits to growth”) if it is to fulfil its promise. While such awareness was then widely suppressed, awareness is reviving, driven by the now obvious perils, not only of climate change but also from weaponization and national aggression. Our neoliberal society (including in academic circles) has inappropriately rewarded articles and researchers that are biased toward optimism. This article proposes six grand (“meta”) challenges that planetary health must face.

KEYWORDS
novel entities, climate change, civilization collapse, limits to growth, optimism bias, population bias, scientific integrity

Introduction

Planetary health is an exciting idea. Over 3,200 other known stars are orbited by planets; many await discovery (1). Even if life proves common, our civilization, created by primates with a complicated family tree (2), is precious. Its durability requires stewardship (3, 4). Yet, it is at risk, particularly from conflict, perhaps worsened by artificial “intelligence”, including “Lethal Autonomous Weapon Systems” (5).

Civilization evolved during the Holocene—the current interglacial, following a much longer Ice Age. Until recently, this was regarded as destined to soon terminate (driven by orbital changes), but increased energy in the Earth system, trapped by rising greenhouse gases, may now postpone this for scores of millennia (6).

Technology has transformed our planet during the Anthropocene, the human-dominated era (4). While this has benefitted most humans (though few other species), some change has been accidental, such as the initial accumulation of greenhouse gases (GHGs). Note that the scale of current GHG emissions can no longer be considered inadvertent. Until recently, it was believed that pollution due to human activities could cause only local harm but it is now understood that the linked Earth–human system has many limits and thresholds, vulnerable to human pollution and other actions (7).

Early recognition of links between human and planetary health

Aspects of Earth system “health” (including nuclear war) have been understood by health workers as relevant to human health for over six decades (8). During the space race, global consciousness that humans share one small planet stimulated seminal books (9). *Silent Spring* (10) warned of the bioaccumulation of synthetic chemicals—biocides—later termed "novel entities" (11) and their risk to ecological and human health. Another was by Dubos, a leading microbiologist (12), who, in the 1960s, developed into a prize-winning biosphere activist and co-authored a book subtitled *The Care and Maintenance of a Small Planet* (13).

In the 1970s, human ecologists published in health journals (14, 15); one (Sargent) warned of "manipulations of the processes of the planetary life support system". Seminal was *The Limits to Growth*, released in 1972 (16). Selling over 12 million copies in 30 languages, its authors used computer modeling to explore interactions among population growth, resource demand, industrialization, food production, and pollution. This study warned that the continuation of existing trends (i.e., that deny the existence of limits) would lead to a marked decline in human wellbeing, including total population size, within a century (9).

In the 1980s, Hansen, a particularly skilled scientific communicator, repeatedly testified to the US Senate concerning climate change (17). His activism is credited as stimulating the first widespread public awakening to this risk.

Leading health journals also paid attention; in 1989, *Lancet* published an inaugural editorial on climate change. However, in 1989, Hansen began to complain of government suppression (17).

Early uses of the term "planetary health"

Prescott et al. have traced the term planetary health to the 1970s, to the "interdependence between human health and place at all scales" (18). They noted that activists called (in 1980) for an expansion of the World Health Organization's (WHO) definition of health to acknowledge that it "involves planetary health". In 1990, King called for incorporating "sustainable" into the same definition (19). He referred to "the health of the planet" and noted the "contribution to planetary ill health" made by the industrialized world. In 1991, Lovelock, best known for the "Gaia" hypothesis, published a book subtitled *The Practical Science of Planetary Medicine* (20). In 1994, epidemiologist McMichael published *Planetary Overload* (21) building, in part, on Sargent's warning about exceeding "life support mechanisms" (15). A 1998 report signified growing WHO recognition of these concepts (22).

In 2014, a "manifesto" of planetary health was published (23), followed by a detailed report (24). Each explicitly warns of "threats to the sustainability of our civilization", while the report reminds readers that "human health and human civilization depend on flourishing natural systems" and their wise stewardship.

Six grand (meta) challenges in planetary health

I next sketch six selected meta-challenges for planetary health. The meaning of "meta", from the Greek, is "to go beyond", such as in "metaphysics", the study of nature at a deeper level. This list is, of course, based on my judgment; it is not intended to be didactic, comprehensive, or exclusive. However, I believe each is very important. These challenges also have relevance beyond planetary health. I call for greater transparency, ethical behavior, and courage to consider the unthinkable—to stimulate policies to avoid civilization's collapse (25).

Reduce self-censorship, challenge power

We need greater scientific courage. Although Earth system indicators are abundant, their interpretation is uncertain and debated, primarily as they involve the future (26). There is growing evidence that Earth system and health scientists have erred toward optimism.

In 2005, soon after my experience with the future scenarios section of the Millennium Ecosystem Assessment (MEA), I published an essay arguing that thresholds are insufficiently factored into models of future population size, leading to absurd projections of maximum human population (26). Hansen has suggested that 'scientific reticence' has delayed public recognition of climate change's risk (27), and others (28) argued that scientists generally err toward reassurance. Only the most secure scientists have been able, consistently, to call for truly fundamental changes in awareness and behavior.

Consequently, substantial parts of the Earth system literature are biased toward optimism (Figure 1), including "negative emission technologies", claiming to rescue us in the near future from catastrophic warming (29, 30). A waltz between money-allocating policymakers (whose loyalty remains overwhelmingly to fossil-fuel companies) and grant-seeking scientists has left future society enormously vulnerable to the failure of unproven strategies. Senior scientific figures who have recognized this include a former director of the Intergovernmental Panel on Climate Change (30). Hansen is also an exception; thus, his forecast that the deliberate pollution of the atmosphere with sulfate aerosols may soon be required to attempt to reduce global heating is disturbing (31).

Supporters of the "precautionary principle" argue for wide safety margins. In many fields, this is uncontroversial: Most nation states have military forces to deter invasion; individuals with means purchase insurance; farmers delay planting until the right season. However, for decades, excuses have been found to avoid and to seek to defer costs and changes necessary to secure planetary health.

This colossal failure has many explanations. One is that the emergency, soon after its recognition, was forecast as maturing in what then seemed the far future—the mid-21st century. A second reason is the vehement, skilled organization of corporation-led opposition, allied with political power, to any attempt to restrain or redefine economic "growth" (32). It has been argued that "climate change is not the result of a market failure but rather the outcome of a fully functioning capital accumulating economy working hard to shift costs on to others" (29).

A third reason is a human genetic and cultural bias toward optimism (33). In addition, humans have limited experience with rapid global environmental change (34). During the transition to the Holocene, sea levels rose by 60 meters over several millennia (35). However, the human population size was then much smaller, and resources were more abundant. Our ancestors prospered in the warmer climate. Warmth is good, but like many natural phenomena (e.g., serum potassium levels), the issue is dose.

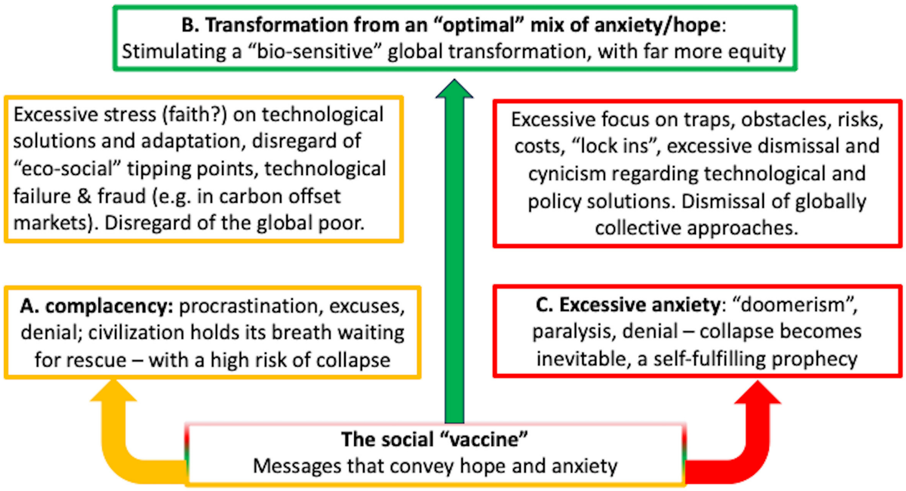

FIGURE 1
Excessive "dose" of either optimism or pessimism is harmful. Adapted from Butler et al. (56).

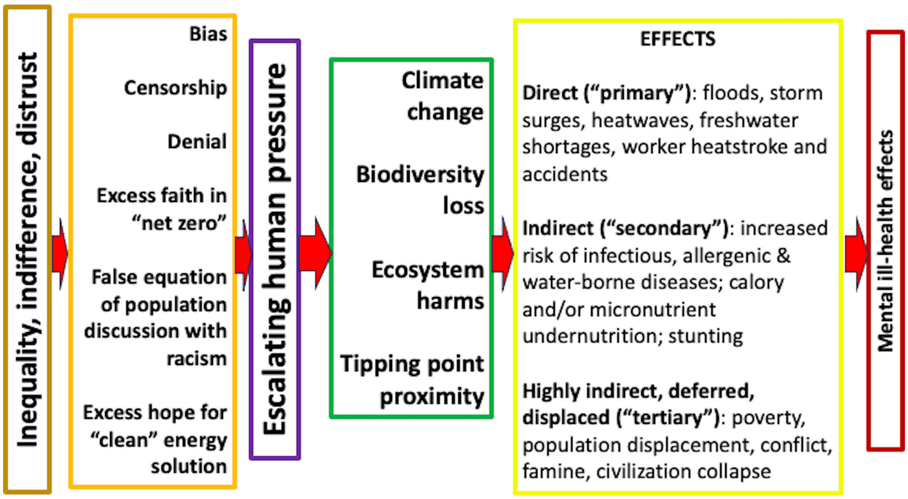

FIGURE 2
Mechanisms by which the harmful effects of ecosystem change can affect human health. Adapted from Corvalan et al. (57) with permission from WHO, which is not responsible for the content or accuracy of this adaptation.

Regard nature as an ally, not a slave or a foe; recover humility

Humans have had incredible success at transforming nature. Catton has argued that this has led to hubris and "overshoot" (36). Piguet (37) has analyzed reasons for the recent disappearance of "environmental considerations" to explain human displacement (now at a record high); he quotes Glacken: "the history of mankind is the history of the conquest of nature" and Beck: a modern society "increasingly develops outside nature." Such pronouncements are naïve.

A paper on the risk to the Mekong delta of inundation via subsidence and sea-level rise calls for revising the "strong belief in human mastery over nature". This delta currently produces 7–10% of all rice traded internationally (38). Its potential flooding is but one of the innumerable problems that we face.

Restore trust in science—Including publishers

Trust in science is vital to winning public support for the radical changes needed to ensure planetary health. Yet, this is falling, including from phenomenal rates of fraud in the scientific literature (39).

Fake research "threatens to overwhelm the editorial processes of a significant number of journals" (39). Another consequence is confusion among early-career researchers and journalists.

Separating published chaff from passable articles is not always easy. How can novices determine flaws in the pyramid of evidence upon which new science sits if many "peer-reviewed" articles are fabricated?

The country of origin of retracted papers has been reported as five times more from the People's Republic of China than from the US (40). A driver for this fraud is excessive reliance for promotion on decisions by the Web of Science, a database controlled by a private corporation (Clarivate) whose processes involved in calculating publishing metrics are criticized as "unscientific and arbitrary" (41). Over-reliance on metrics to assess merit is highly problematic. Loss of confidence in science is further amplified by "mega" (42) and "predatory" publishers.

Foster nuanced, mutually respectful discussions about population and consumption

The issues of population (including growth rates and absolute numbers) and resource consumption have long been understood as integral to planetary health. However, many misconceptions remain, including some propagated in a recent major report of the UN Population Fund (UNFPA) (43). In this, UNFPA's executive director asserted that its second key message is to "shatter the myth" that experts "blame fertility rates for the climate crisis" (44). To the contrary, experts overwhelmingly attribute climate change mostly to the behavior of populations in high-income settings, including via their purchase of products from the global south. Most scholarly concern about high population growth rates in "developing" countries focuses on consequences for poverty, hunger, vulnerability to climate change, and other aspects of impaired planetary health (45).

Clearer discussion of links between conflict, displacement, and planetary health

Neither paper that revived the term planetary health (23, 24) has much discussion of conflict or population displacement. However, one (24) reproduces a figure that groups health effects into three classes (Figure 2). The third category includes conflict. This typology has the advantage of identifying a hierarchy of effects among the thousands of adverse health consequences of failing planetary health (46).

Recent planetary health papers acknowledge debts to the literature on planetary and Earth system boundaries (47) and thus to the Limits to Growth (48). However, as yet, there has been little conceptual development of the risk to health from conflict or population displacement as regional and global limits are approached or breached (49). A likely reason for this self-censorship is fear of disciplinary transgression; another may be fear of causing excess concern. If so, that is unwarranted—risks need accurate forecasts to be reduced (25).

Stronger regulation of synthetic biology and bioweapon capacity

Synthetic biology includes the genetic modification of organisms and viruses. Modern capacity for this extends far beyond the selective breeding of plants (and gene insertion in laboratories), seeking to enhance global food security. It also includes the manipulation—and even the creation—of known and novel pathogens, some of which might cause pandemics. The risk from such "biohazards" was recognized in 1975 at the first Asilomar Conference (50). A summary statement from this meeting agreed to confine some experiments to highly secure laboratories to reduce risk. Since then, however, the power of synthetic biology has increased immeasurably, and many pathogen leaks have occurred from supposedly secure laboratories (51).

In 2018, researchers reported the synthesis of horsepox from chemically synthesized DNA fragments. They explained they did this to show that synthesis of variola (which causes smallpox) is now possible (52). The creation of novel pathogens is relevant to planetary health not only because COVID-19 has shown how harmful pandemics can be to global wellbeing but also because such pathogens, if previously unknown in nature, are novel entities, one of the planetary boundaries (53). The origin of SARS-CoV-2 remains unknown (54, 55); continued downplaying its possible laboratory origin also undermines public trust in science.

Conclusion

The planetary health emergency is deepening. Excellent research can inform policymakers on ways to reduce our common peril.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CB: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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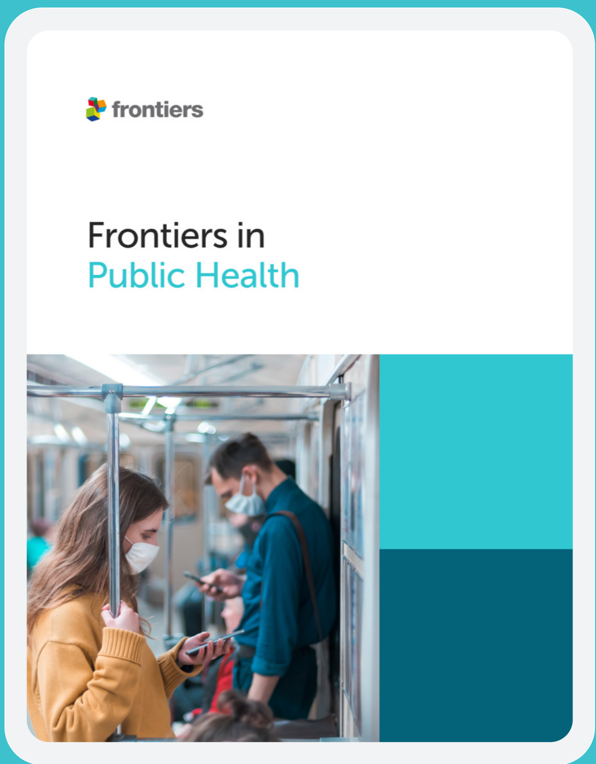

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