# A just world on a safe planet: a *Lancet Planetary Health*–Earth Commission report on Earth-system boundaries, translations, and transformations

*Joyeeta Gupta, Xuemei Bai, Diana M Liverman, Johan Rockström, Dahe Qin, Ben Stewart-Koster, Juan C Rocha, Lisa Jacobson, Jesse F Abrams, Lauren S Andersen, David I Armstrong McKay, Govindasamy Bala, Stuart E Bunn, Daniel Ciobanu, Fabrice DeClerck, Kristie L Ebi, Lauren Gifford, Christopher Gordon, Syezlin Hasan, Norichika Kanie, Timothy M Lenton, Sina Loriani, Awaz Mohamed, Nebojsa Nakicenovic, David Obura, Daniel Ospina, Klaudia Prodani, Crelis Rammelt, Boris Sakschewski, Joeri Scholtens, Thejna Tharammal, Detlef van Vuuren, Peter H Verburg, Ricarda Winkelmann, Caroline Zimm, Elena Bennett, Anders Bjørn, Stefan Bringezu, Wendy J Broadgate, Harriet Bulkeley, Beatrice Crona, Pamela A Green, Holger Hoff, Lei Huang, Margot Hurlbert, Cristina Y A Inoue, Şiir Kılkış, Steven J Lade, Jianguo Liu, Imran Nadeem, Christopher Ndehedehe, Chukwumerije Okereke, Ilona M Otto, Simona Pedde, Laura Pereira, Lena Schulte-Uebbing, J David Tàbara, Wim de Vries, Gail Whiteman, Cunde Xiao, Xinwu Xu, Noelia Zafra-Calvo, Xin Zhang, Paola Fezzigna, Giuliana Gentile*

## Executive summary

The health of the planet and its people are at risk. The deterioration of the global commons—ie, the natural systems that support life on Earth—is exacerbating energy, food, and water insecurity, and increasing the risk of disease, disaster, displacement, and conflict. In this Commission, we quantify safe and just Earth-system boundaries (ESBs) and assess minimum access to natural resources required for human dignity and to enable escape from poverty. Collectively, these describe a safe and just corridor that is essential to ensuring sustainable and resilient human and planetary health and thriving in the Anthropocene. We then discuss the need for translation of ESBs across scales to inform science-based targets for action by key actors (and the challenges in doing so), and conclude by identifying the system transformations necessary to bring about a safe and just future.

Our concept of the safe and just corridor advances research on planetary boundaries and the justice and Earth-system aspects of the Sustainable Development Goals. We define safe as ensuring the biophysical stability of the Earth system, and our justice principles include minimising harm, meeting minimum access needs, and redistributing resources and responsibilities to enhance human health and wellbeing. The ceiling of the safe and just corridor is defined by the more stringent of the safe and just ESBs to minimise significant harm and ensure Earth-system stability. The base of the corridor is defined by the impacts of minimum global access to food, water, energy, and infrastructure for the global population, in the domains of the variables for which we defined the ESBs. Living within the corridor is necessary, because exceeding the ESBs and not meeting basic needs threatens human health and life on Earth. However, simply staying within the corridor does not guarantee justice because within the corridor resources can also be inequitably distributed, aggravating human health and causing environmental damage. Procedural and substantive justice are necessary to ensure that the space within the corridor is justly shared.

We define eight safe and just ESBs for five domains—the biosphere (functional integrity and natural ecosystem area), climate, nutrient cycles (phosphorus and nitrogen), freshwater (surface and groundwater), and aerosols—to reduce the risk of degrading biophysical life-support systems and avoid tipping points. Seven of the ESBs have already been transgressed: functional integrity, natural ecosystem area, climate, phosphorus, nitrogen, surface water, and groundwater. The eighth ESB, air pollution, has been transgressed at the local level in many parts of the world. Although safe boundaries would ensure Earth-system stability and thus safeguard the overall biophysical conditions that have enabled humans to flourish, they do not necessarily safeguard everyone against harm or allow for minimum access to resources for all. We use the concept of Earth-system justice—which seeks to ensure wellbeing and reduce harm within and across generations, nations, and communities, and between humans and other species, through procedural and distributive justice—to assess safe boundaries. Earth-system justice recognises unequal responsibility for, and unequal exposure and vulnerability to, Earth-system changes, and also recognises unequal capacities to respond and unequal access to resources.

We also assess the extent to which safe ESBs could minimise irreversible, existential, and other major harms to human health and wellbeing through a review of who is affected at each boundary. Not all safe ESBs are just, in that they do not minimise all significant harm (eg, that associated with the climate change, aerosol, or nitrogen ESBs). Billions of people globally do not have sufficient access to energy, clean water, food, and other resources. For climate change, for example, tens of millions of people are harmed at lower levels of warming than that defined in the safe ESB, and thus to avoid significant harm would require a more stringent ESB. In other domains, the safe ESBs align with the just ESBs, although some need to be modified, or complemented with local standards, to prevent significant harm (eg, the aerosols ESB).

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**Amsterdam Institute for Social Science Research, University of Amsterdam, Amsterdam, Netherlands** (Prof J Gupta PhD, D Ciobanu MSc, K Prodani MSc, C Rammelt PhD, J Scholtens PhD, P Fezzigna MSc, G Gentile MSc); **IHE-Delft Institute for Water Education, Delft, Netherlands** (Prof J Gupta); **Fenner School of Environment & Society, Australian National University, Canberra, ACT, Australia** (Prof X Bai PhD, S J Lade PhD); **School of Geography, Development and Environment, University of Arizona, Tucson, AZ, USA** (Prof D M Liverman PhD, L Gifford PhD); **Potsdam Institute for Climate Impact Research, Leibniz Association, Potsdam, Germany** (Prof J Rockström PhD, L S Andersen PhD, S Loriani PhD, B Sakschewski PhD, Prof R Winkelmann PhD); **Institute of Environmental Science and Geography** (Prof J Rockström) **and Institute of Physics and Astronomy** (Prof R Winkelmann), **University of Potsdam, Potsdam, Germany; State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China** (Prof D Qin PhD, Prof C Xiao PhD); **China Meteorological Administration, Beijing, China** (Prof D Qin, X Xu PhD); **University of Chinese Academy of Sciences, Beijing, China**

(Prof D Qin, X Xu); **Australian Rivers Institute, Griffith University, Brisbane, QLD, Australia** (B Stewart-Koster PhD, Prof S E Bunn PhD, S Hasan PhD, C Ndehedehe PhD); **Future Earth Secretariat, Stockholm, Sweden** (J C Rocha PhD, L Jacobson MSc, D Ospina MSc, W J Broadgate PhD, S J Lade, S Pedde PhD); **Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden** (J C Rocha, D I Armstrong McKay PhD, Prof B Crona PhD, S J Lade, L Pereira PhD); **Global Systems Institute** (J F Abrams PhD, D I Armstrong McKay, Prof T M Lenton PhD) **and Business School** (Prof G Whiteman PhD), **University of Exeter, Exeter, UK; Georesilience Analytics, Leatherhead, UK** (D I Armstrong McKay); **Center for Atmospheric and Oceanic Sciences** (Prof G Bala PhD) **and Interdisciplinary Centre for Water Research** (T Tharammal PhD), **Indian Institute of Science, Bengaluru, India; EAT, Oslo, Norway** (F DeClerck PhD); **Alliance of Bioversity and CIAT, CGIAR, Montpellier, France** (F DeClerck); **Center for Health & the Global Environment, University of Washington, Seattle, WA, USA** (Prof K L Ebi PhD); **Institute for Environment and Sanitation Studies, University of Ghana, Legon, Ghana** (Prof C Gordon PhD); **Graduate School of Media and Governance, Keio University, Fujisawa, Japan** (Prof N Kanie PhD); **Functional Forest Ecology, University of Hamburg, Hamburg, Germany** (A Mohamed PhD); **International Institute for Applied Systems Analysis, Laxenburg, Austria** (Prof N Nakicenovic PhD, C Zimm PhD); **Coastal Oceans Research and Development in the Indian Ocean East Africa, Mombasa, Kenya** (D Obura PhD); **Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands** (Prof D van Vuuren PhD, Prof H Bulkeley PhD); **PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands** (Prof D van Vuuren,

## *Panel 1:* Glossary

*ESBs:* Quantitative (when possible) and qualitative descriptions of boundaries beyond which the stability and resilience of Earth-system processes is threatened and humans might be substantially harmed. ESBs go beyond planetary boundaries by combining elements from the local to global level with knowledge from biophysical and social science domains.

*Safe ESBs*: ESBs that, if adhered to, would maintain and enhance the biophysical stability of the Earth system over time, thereby safeguarding the Earth system's functions and ability to support humans and all other living organisms.[10]

*Just ESBs*: ESBs that, if adhered to, would ensure an Earth-system state that minimises the risk of significant harm to present and future generations, countries, and communities. Just ESBs can be expanded to minimise risk to species and ecosystems.

*Earth-system justice*: Building on epistemic justice and local-to-global justice scholarship, Earth-system justice includes procedural justice (access to information, decision-making, civic space, and courts) and substantive justice in terms of ensuring access to basic resources and services while ensuring no significant harm and allocation of the remaining resources, risks, and responsibilities. Achieving Earth-system justice involves multiple, systemic transformations that address drivers of Earth-system change and vulnerability, and includes addressing the barriers to, and responsibility for, such changes. It also requires addressing the mechanisms that govern the allocation of resources, as well as identifying who is responsible for Earth-system change, and how.[11] The scope of Earth-system justice is framed by three overarching criteria: interspecies justice, intergenerational justice, and intragenerational justice.

*Safe and just corridor:* A clearly defined space in which pathways of future human development are both safe and just over time, and that acknowledges that the Earth's natural resources (including carbon, nutrients, water, and land) are finite and have to be justly shared between people and nature.[12] The ESBs[10] we have defined provide the ceiling of the corridor, and the total pressure on the Earth system if all people have minimum access to basic resources[13] is the base.

*Global commons*: The "planet's natural resources—the ecosystems, biomes and processes that regulate the stability and resilience of the Earth system".[14] The stability and resilience of the Earth system is vital to all and dependent upon the global commons. Local commons across the planet are fundamental building blocks of the global commons.

*Just minimum access*: Minimum access refers to the level of essential necessary resources and services (eg, water, food, energy, infrastructure) that all people are entitled to.
Two different levels have been quantified for each Earth-system domain. Level 1 (dignity) describes the minimum access needed to lead a basic dignified life beyond mere survival (including, for example, access to a toilet). Level 2 describes a higher level of minimum access to resources that would be needed to enable an escape from poverty.

ESBs=Earth-system boundaries.

We examine the implications of achieving the social SDGs in 2018 through an impact modelling exercise, and quantify the minimum access to resources required for basic human dignity (level 1) as well as the minimum resources required to enable escape from poverty (level 2). We conclude that without social transformation and redistribution of natural resource use (eg, from top consumers of natural resources to those who currently do not have minimum access to these resources), meeting minimum-access levels for people living below the minimum level would increase pressures on the Earth system and the risks of further transgressions of the ESBs.

We also estimate resource-access needs for human populations in 2050 and the associated Earth-system impacts these could have. We project that the safe and just climate ESB will be overshot by 2050, even if everybody in the world lives with only the minimum required access to resources (no more, no less), unless there are transformations of, for example, the energy and food systems. Thus, a safe and just corridor will only be possible with radical societal transformations and technological changes.

Living within the safe and just corridor requires operationalisation of ESBs by key actors across all levels, which can be achieved via cross-scale translation (whereby resources and responsibilities for impact reductions are equitably shared among actors). We focus on cities and businesses because of the magnitude of their impacts on the Earth system, and their potential to take swift action and act as agents of change. We explore possible approaches for translating each ESB to cities and businesses via the sequential steps of transcription, allocation, and adjustment. We highlight how different elements of Earth-system justice can be reflected in the allocation and adjustment steps by choosing appropriate sharing approaches, informed by the governance context and broader enabling conditions.

Finally we discuss system transformations that could move humanity into a safe and just corridor and reduce risks of instability, injustice, and harm to human health. These transformations aim to minimise harm and ensure access to essential resources, while addressing the drivers of Earth-system change and vulnerability and the institutional and social barriers to systemic transformations, and include reducing and reallocating consumption, changing economic systems, technology, and governance.

## Introduction

Planetary health is acutely under threat in the Anthropocene, with the causes and impacts of this threat inequitably distributed.[1] Roughly 9 million premature deaths annually are linked to exposure to air and water pollution, 3·2 billion people are affected by land degradation, and many millions are affected by zoonotic disease, rising temperatures, and extreme weather events.[2–5] People living in historically marginalised locations (eg, former colonies), especially people living in poverty, are particularly at risk. Economic growth trajectories (which dominate global economic policy) pose even greater risks through destabilisation of the global commons—ie, the biosphere, climate, and cryosphere, and nutrient and water cycles.[1,6–9] Integration of socioeconomic concerns into Earth-system boundaries (ESBs)—limits that should be adhered to in order to maintain the stability of the planet and safety of humans[10]—will facilitate reaching a stable state of the Earth system and thereby promote human health and wellbeing (panel 1).

This Commission reports on work from the Earth Commission, an international, transdisciplinary group of scholars that informs the creation of science-based targets and transformations to protect critical global commons. This work seeks to define safe and just ESBs intended to guide human development across eight dimensions for five Earth-system domains—climate, biosphere (functional integrity and natural ecosystem area), freshwater (surface and ground), nutrient cycles (nitrogen and phosphorus), and aerosols. The ESBs are defined at the global scale, with some derived and aggregated from local-scale boundaries (eg, river basin scale), making them operational at subglobal levels (from regional to local). Our ESBs integrate Earth-system and social and health perspectives by using, for the first time, the same units of quantification for both.

Identification of safe ESBs is essential for governing the local to the global commons and for protecting planetary health. Transgression of safe boundaries in the Amazon or Arctic regions, for example, could affect the ability of future generations to live healthy lives and prosper,[8,15,16] and of nations to achieve the UN's Sustainable Development Goals (SDGs). Although defining safe ESBs is intended to maintain Earth-system stability, remaining within these boundaries will not necessarily prevent harm to human health. A justice approach, by contrast, requires at least boundaries that minimise significant harm to human health and wellbeing and to other species (panel 2) while ensuring access to necessary resources and services. Current environmental pressures are highly unequal, with the richest 10% of the global population consuming as much energy as the poorest 80%[17] and being responsible for more emissions than the other 90%.[18] Between 23% and 62% of the global population does not have adequate access to resources to meet basic needs.[13] The inequalities are stark between the wealthiest regions (eg, North America, Europe, Australia) and the poorest regions (eg, sub-Saharan Africa, South Asia, Central America). Meeting the critical material needs of people who currently do not have the minimum required access to resources without transformations and redistribution of resources would increase the pressure on the Earth system.[13] Thus, ensuring Earth-system stability and resilience requires addressing issues of social justice, underlying drivers and pressures, and distributional and technical aspects of how resources are produced, distributed, and consumed.

### *Panel 2*: Defining significant harm

- Harm: negative effects (including on health) on humans, communities, and countries as a result of Earth-system changes due to human activities pushing the Earth system outside of the safe and just Earth-system boundaries.
- Significant harm: existential or irreversible negative effects on people, communities, or countries, such as substantial loss of life, deterioration of health, chronic disease, injury, malnutrition, displacement, loss of livelihood or income, loss of access to nature's contributions to people, or loss of land.
- No significant harm principle: states and other actors responsible for anthropogenic Earth-system change have a duty to refrain from causing significant harm; to prevent, reduce, and control the risk of causing significant harm; and to repair or compensate for significant harm already inflicted.

In this Commission, we define a safe and just corridor (panel 1) with a ceiling defined by the more stringent of the safe and just ESBs (ie, the lower of the two ESBs).[10] The base of this corridor estimates the effects on Earth-system domains of meeting minimum access levels to necessary resources and services (eg, water, food, energy, infrastructure) for all people, which allows consistent assessment of the corridor space within which justice, health, and wellbeing is possible for current and future generations (figure 1).

Under current social and environmental conditions, all humans cannot live healthy lives within the safe and just corridor.[13] Systemic transformations of underlying drivers of Earth-system change and vulnerability is needed to reduce harm and to enable everyone to live within this corridor. An Earth-system justice approach (panel 1), which offers an analytical and evaluative tool consisting of just ends (targets) and just means (levers), could enable living within the ESBs.[11,19] Transformations would require mobilisation of societal actors who, informed by knowledge of their fair shares of ESBs through cross-scale translation, act to limit their resource

L Schulte-Uebbing PhD); **Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland** (Prof P H Verburg PhD); **Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, Netherlands** (Prof P H Verburg); **Bieler School of Environment and Department of Natural Resource Sciences, McGill University, Montreal, QC, Canada** (Prof E Bennett PhD); **Centre for Absolute Sustainability and Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Kongens Lyngby, Denmark** (A Bjørn PhD); **Center for Environmental Systems Research, University of Kassel, Kassel, Germany** (Prof S Bringezu PhD); **Department of Geography, Durham University, Durham, UK** (Prof H Bulkeley); **Global Economic Dynamics and the Biosphere Programme, Royal Swedish Academy of Sciences, Stockholm, Sweden** (Prof B Crona); **Advanced Science Research Center at the Graduate Center, City University of New York, NY, USA** (P A Green ME); **Wegener Center for Climate and Global Change, University of Graz, Graz, Austria** (H Hoff PhD, Prof I M Otto PhD); **National Climate Center, Beijing, China** (L Huang PhD); **Johnson-Shoyama Graduate School of Public Policy, University of Regina, Regina, SK, Canada** (Prof M Hurlbert PhD); **Center for Global Studies, Institute of International Relations, University of Brasília, Brasília, Brazil** (C Y A Inoue PhD); **Institute for Management Research, Radboud University, Nijmegen, Netherlands** (C Y A Inoue); **Scientific and Technological Research Council of Turkey, Ankara, Türkiye** (Prof Ş Kılkış PhD); **Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA** (Prof J Liu PhD); **Institute of Meteorology and Climatology, Department of Ecosystem Management, Climate and Biodiversity, BOKU University, Vienna, Austria** (I Nadeem PhD);

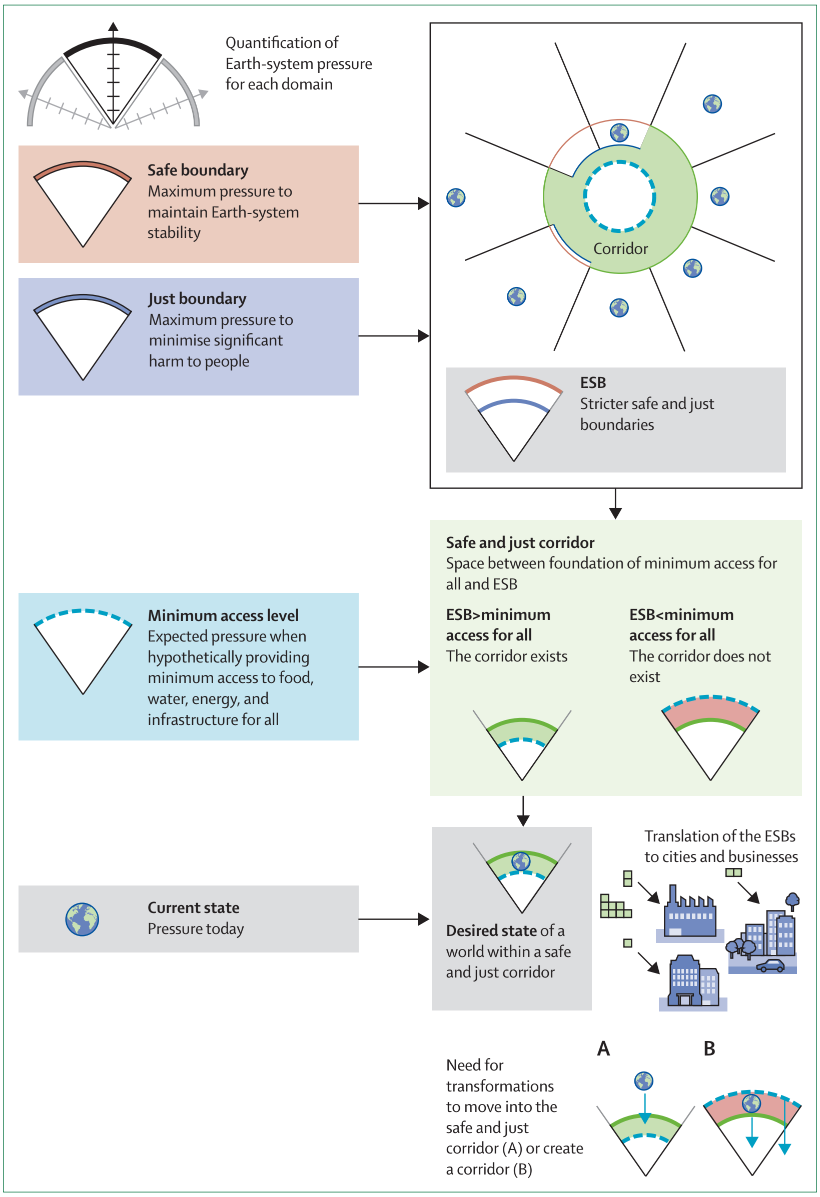

*Figure 1:* **Visualisation of the concept of the safe and just corridor**
We quantified eight safe and just ESBs, indicating the maximum pressure that can be exerted on that domain that is both safe and just for people and the planet. These ESBs form the ceiling of a safe and just corridor, for which the base is the level of pressure that would be exerted on the Earth system to ensure universal provision of minimum access to food, water, energy, and infrastructure. ESB=Earth-system boundary.

**School of Environment & Science, Griffith University, Nathan, QLD, Australia** (C Ndehedehe); **School of Policy Studies, University of Bristol, Bristol, UK** (Prof C Okereke PhD); **Soil raphy and Landscape Group** (S Pedde) **and Environmental Systems Analysis Group** (L Schulte-Uebbing, Prof W de Vries PhD), **Wageningen University &**

use and broader impact on the planet. Cities and businesses are key actors driving anthropogenic pressures, but have received less attention in sustainability assessments than countries. The unique challenges associated with these actors need to be understood and resolved in translation methods, and approaches that reflect the specific environmental, social, and economic contexts of cities and businesses need to be developed. We discuss how ESBs can be translated across scales (ie, from individuals to cities, businesses, organisations, countries, and other administrative and political boundaries), aiming to assign ESB-aligned resource budgets and responsibilities equitably, with components of distributional justice addressed through the iterative process of allocation and adjustment. We also assess how Earth-system justice can be reflected in these allocations via sharing approaches, efficient governance, and enabling conditions for cities and businesses to implement cross-scale translation.

Other frameworks on anthropogenic pressures include the Limits to Growth,[20,21] the 2001 Amsterdam Declaration on Earth Systems Science,[22] Planetary Boundaries,[7,9] the UN 2030 Agenda (and associated SDGs),[6] and Doughnut Economics[23,24] (developed in response to Planetary Boundaries). Whereas Planetary Boundaries only assess safe biophysical boundaries at the global scale, Doughnut Economics combines the nine Planetary Boundaries with 12 human and social foundations to create a safe and just space for humanity. Although Doughnut Economics' safe and just indicators[25] include justice elements, our work goes further by quantifying these elements in the same units as the safe ESBs and by operationalising and quantifying justice issues.[26,27] Consumption corridors[28,29] are a related concept, but the Earth Commission takes a more holistic Earth-system approach.

We build upon SDGs[6] that aspire towards a fundamentally new direction of development for the benefit of all people and the planet. We further operationalise the SDGs by providing the scientific underpinning for identifying the safe and just corridor that needs to be achieved to avoid triggering events that have irreversible impacts on the biophysical systems in the Earth system and significant harm to people while assuring that all people have access to basic needs such as water, energy, and food. Our translation framework builds on existing approaches[30,31] to incorporate social and environmental impacts and the socioeconomic and ecological context, reflecting equity and justice principles. We build on transformation scholarship,[32–34] with an increased focus on drivers that push humanity outside the safe and just corridor.[35]

The remainder of this Commission is organised into four parts (figure 1). In part 1, we describe our theoretical framework and methods. In part 2, we present the quantifications of safe and just ESBs with a spatially explicit approach that allow identification of where ESBs are transgressed and which people are most exposed to associated deleterious effects on health and other harms. We also quantify the base and ceiling of the safe and just corridor in the same units for today and 2050, with the base representing the impact on the Earth system if all people had equal access to a minimum level of resources and the ceiling defined by the safe and just ESBs. In part 3, we discuss challenges, approaches, and enabling conditions in translating the ESBs to cities and businesses, and in part 4 we identify fundamental transformations needed to keep humanity within the safe and just corridor.

## Part 1: Theoretical framework and methods—safe and just ESBs

### Safe ESBs

Safe ESBs define the conditions that would maintain a stable and resilient Earth system. During the Holocene, which began around 12 000 years ago,[36] Earth-system stability enabled the development of agriculture and complex human societies.[37] Human impacts on the Earth system, particularly in the past few hundred years, have accelerated as a result of land clearing, colonisation, and the Industrial Revolution, with its reliance on fossil fuels and increased trade. After 1950, increases in chemical use, production, and consumption further accelerated the pace of change in a so-called great acceleration identified with the Anthropocene epoch.[13,38]

The Anthropocene is characterised by climate change, widespread pollution, and biodiversity loss, undermining human health and wellbeing by altering life-support systems. Only with Holocene-like climate stability can the Earth system reliably provide conditions that support the health and livelihoods of billions of people.[39] Other types of climate, such as a glacial ice age or the so-called hothouse Earth (which might be induced by unchecked emissions or by strong feedbacks and tipping dynamics),[40] would be less habitable. As temperature thresholds are crossed, elements of the Earth system could tip into unstable conditions that would threaten wellbeing and survival[7,9]—eg, the loss of boreal permafrost and the Greenland ice sheet would irreversibly change the Earth system, including the global hydrological cycle.[15] Exceeding tipping points in one part of the world could trigger changes in ecosystems and societies elsewhere, potentially reducing the provision of ecosystem services (ie, the benefits provided by healthy ecosystems to humans), disrupting supply chains, and compromising Earth-system stability.[41]

Emerging Earth-system changes risk crossing tipping points and causing other declines in critical Earth-system functions. Use of a Holocene-like environment as a reference state for climate helps define safe conditions, but for changes in other Earth-system domains that affect humanity at a more local scale, alternative reference points are necessary—eg, for blue-water flows, for which there has been substantial spatiotemporal variability, including variations in tropical monsoons,[42] affected humans and aquatic ecosystems.[43] For such domains, prevention of the crossing of local tipping points that would negatively affect humans, such as local ecosystem collapse, provides a basis for defining what is safe (as well as just).

Past and present actions commit humanity to future outcomes. Unless steep cuts are made in greenhouse gas emissions, global average temperatures will increase to 1·5°C above pre-industrial temperatures by the early 2030s.[3] Continued exceeding of safe boundaries in other domains will probably have critical, sometimes irreversible, effects on ecosystems and human health in the near term—eg, ongoing extraction of groundwater beyond replenishment can lead to land subsidence and damage that would affect health through multiple pathways.

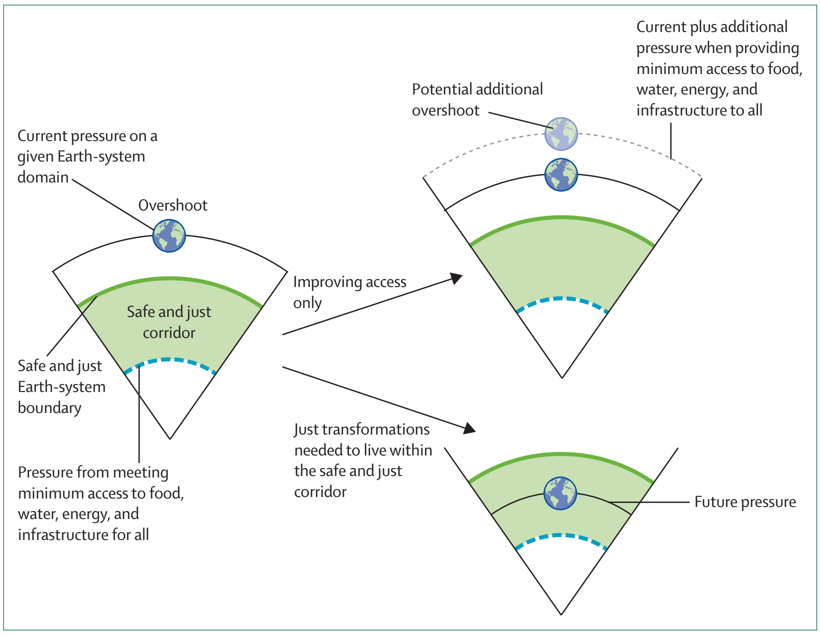

*Figure 2:* **Current transgression of Earth-system boundaries and potential impact of future actions**
Earth-system boundaries have already been transgressed in many domains. Providing minimum access to food, water, energy, and infrastructure to people without access will further increase this pressure unless just transformations to enable living within the safe and just corridor are prioritised.

### Just ESBs: conceptualising Earth-system justice

The significant and uneven harm (panel 2) that environmental degradation causes to human health and wellbeing means that an Earth-system justice approach is needed to identify fair solutions to the interrelated environmental crises.[11,19,44] Just ESBs are generally more stringent than safe ESBs and aim to prevent significant harm to the health and wellbeing of humans and natural systems (figure 2). Stringent ESBs that prevent environmental degradation and associated effects on human health via climate change and air and water pollution could also affect some people's access rights to land, water, and other resources, nature's services, decent livelihoods, and wellbeing, especially in low-income countries,[45] further exacerbating the injustice that billions of people do not have access to minimum required resources. These are also the very people who have caused the least environmental damage. However, improving access to basic resources and services would increase the pressure on, and contribute to crossing ESBs unless there are profound changes that reduce and redistribute excess consumption or otherwise reduce pressures (eg, appropriate technological and institutional innovations).[13] Such redistribution can only be addressed by just transformations that enable meeting the minimum needs of all, through sustainable technologies, respecting human rights, value changes, and governance, and by

**Research, Wageningen, Netherlands; Global Change Institute, University of the Witwatersrand, Johannesburg, South Africa** (L Pereira)**; Autonomous University of Barcelona, Barcelona, Spain** (J D Tàbara PhD)**; Global Climate Forum, Berlin, Germany** (J D Tàbara)**; State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China** (Prof C Xiao)**; Basque Centre for Climate Change, Scientific Campus of the University of the Basque Country, Biscay, Spain** (N Zafra-Calvo PhD)**; Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, USA** (Prof X Zhang PhD)

Correspondence to:
Dr Juan C Rocha, Stockholm Resilience Centre, Stockholm University, Stockholm 10691, Sweden
**juan.rocha@su.se**

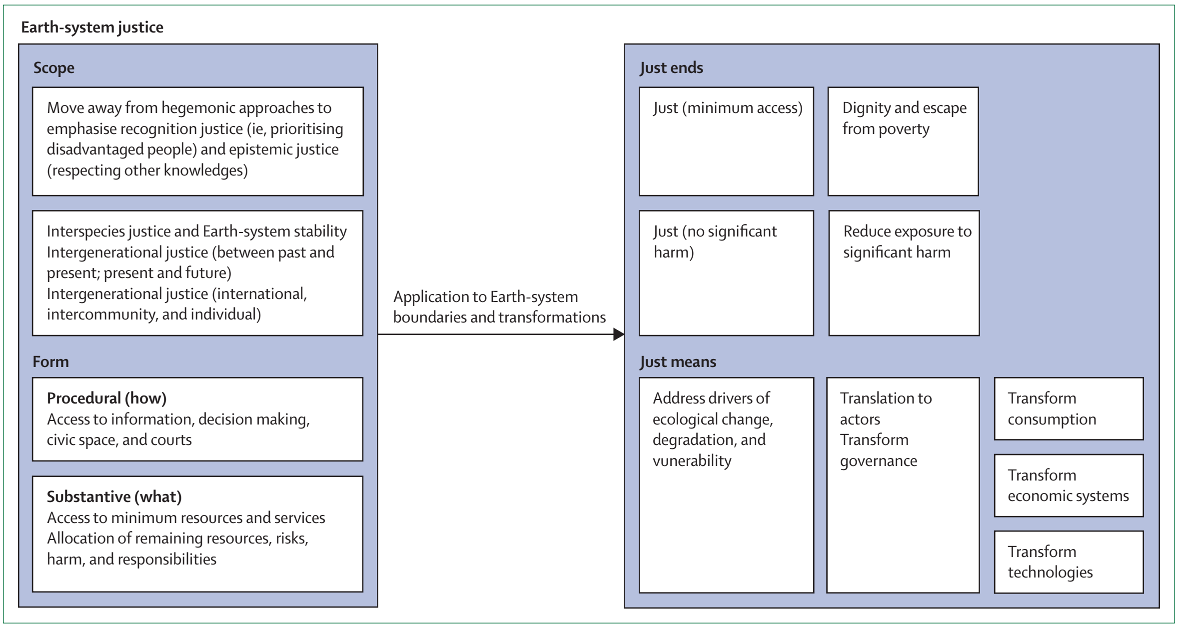

*Figure 3:* **Conceptualising and operationalising Earth-system justice**
Modified from Gupta et al, 2023.[11]

redistributing resources to enable all to live equitably and healthily within the safe and just ESBs (figure 2).

Our Earth-system justice framework[11] builds on diverse justice conceptualisations[46] from local to planetary levels[26,47] and from incremental reforms to systemic transformations. Incremental policies are unlikely to address systemic problems and their underlying drivers, and thus systemic and just transformations are needed.[48] We conceptualise Earth-system justice as incorporating local through to global justice because social–ecological interactions play out across scales.[49]

We distinguish recognition justice[50] from epistemic[51–53] justice (figure 3). Recognition justice requires that the power structures and institutionalised norms that marginalise individuals and groups should be addressed, for example, by inclusion of the knowledge and views of marginalised people in decisions about safe and just boundaries and enabling their participation in processes of decision making.[54] Epistemic justice involves recognising and including multiple forms of knowledge, including that of Indigenous and local communities and the most marginalised and vulnerable people, in science and decision making.[55] Recognition and epistemic justice underpin our focus on the most marginalised and vulnerable peoples.

Our scope of justice is framed by three overarching criteria: interspecies justice and Earth-system stability, intergenerational justice, and intragenerational justice. Interspecies justice and Earth-system stability[56] involves identifying how to prevent significant harm to species and to the stability of the Earth's systems that support them. Intergenerational justice refers to justice between past and present generations, and between present and future people—eg, earlier generations who used up carbon budgets or made species extinct should compensate those who experience loss and damage because of the resulting climate change or biodiversity loss.[57,58] Intragenerational justice refers to justice within generations, with emphasis on the most vulnerable people,[57] and seeks fairness between individuals, communities, and nations through meeting minimum needs or reducing suffering.

Intragenerational justice can be further broken down into international, intercommunity, and individual justice. International justice comprises transboundary justice issues, such as limited territorial sovereignty, which allows countries to use their own resources but not to cause harm to other places,[59] and equitable sharing of transboundary resources, such as rivers.[60,61] It includes the common but differentiated responsibilities and respective-capabilities principle in climate change that requires countries that emitted more in the past, and those that are better resourced, to take greater responsibility for financing mitigation of emissions, funding adaptation to climate change, and compensating for losses and damages from climate impacts.[62] International justice also encompasses the access, benefit sharing, and differential national circumstances principles in protecting biodiversity.[63–65] Intercommunity justice refers to how different communities affect each other and share responsibility and resources,[66] while individual justice looks at how humans are affected by environmental degradation and the actions of others and the differences in individual responsibility, impacts, and responses.[67]

We consider intergenerational and intragenerational justice through the lens of intersectional justice, which acknowledges that poverty, vulnerability, and exposure to environmental impacts are associated with multiple identities and disadvantages, including lack of recognition, lack of representation (ie, the exclusion of specific groups from local and global discussion forums), and structural inequalities that make people vulnerable or lead to their exclusion.[68–70] Discrimination based on ethnocultural heritage, gender, age, and socioeconomic status can be collectively and multiply experienced by individuals and communities.[71] Our framework (figure 3) includes procedural justice (eg, access to information, decision making, civic space, and courts), and substantive justice regarding the principles, instruments and mechanisms, and organisations that are set up to address a problem. Recognition and intersectional justice might require additional support for marginalised people to enable their effective participation[72] and to address specific power relations.

We analyse justice in terms of means and ends. Just means are the processes and transformations needed to keep everyone within safe and just ESBs. Just ends include ensuring that all humans have minimum access to resources and services to meet their basic needs to be able to live a basic, dignified life or to escape from poverty, and ensuring that people, communities, and countries can be protected from the irreversible and existential harm of environmental degradation. Both of these ends aim to protect the health of people.

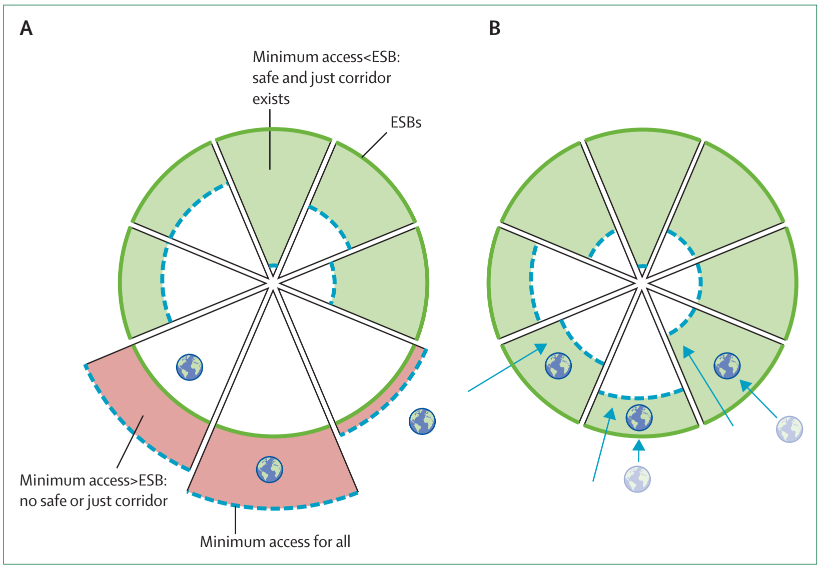

***Figure 4:*** **Conceptualisation of the different potential states of the safe and just corridor**
Both (A) and (B) are representations of the Earth system, divided into eight to represent the eight dimensions (across five domains) for which we calculated ESBs. The ceiling for each domain is represented by green lines at the outer edge, while the base is represented by the blue dashed lines. (A) A world without a safe and just corridor in some domains because ensuring minimum access level 2 (no more, no less) for everyone would lead to the base of the corridor exceeding the ESBs. The pressure on the Earth system, represented by the globes, can be inside or outside the corridor, depending on whether minimum access is provided to all people or not. (B) The desired state of the planet after systemic transformations that provide minimum level 2 for all people within the ESBs. These systemic transformations, represented by the blue arrows, enable the formation of a safe and just corridor, thereby reducing current pressure on the Earth system.

## Methods

Our conceptual framing of Earth-system justice[11] defines a safe and just corridor, with the ESBs[10] as the ceiling and levels of minimum access[13] as the base. We first define the safe and just ESBs and analyse the spatial distribution of where they are transgressed, along with the populations exposed to those conditions and their vulnerability (using poverty as a proxy). We then use the framework and results of Rammelt and colleagues[13] to estimate the impact on the Earth system in 2050 of providing minimum access to resources to people who do not have access as of 2018.

Methods for quantification of safe ESBs are based on syntheses of scientific literature, modelling, and global-scale analyses, and differ from domain to domain.[10] These boundaries are global aggregates, derived from bottom-up and top-down approaches, or build on uniformly applicable standards that enable the identification of critical places for Earth-system stability and human wellbeing (eg, key biomes that regulate the climate system, such as the Amazon rainforest). The domains that are derived from bottom-up approaches have sub-global ESBs where a boundary exists at finer scales and can be aggregated globally (eg, river-basin scale for surface water that is aggregated to a global ESB). Data sources for mapping are in the appendix (p 13); the derivation of the safe ESBs was described by Rockström and colleagues.[10]

Just ESBs are boundaries that safeguard people from significant harm now and in the future. We define significant harm as widespread and severe, existential, or irreversible negative impacts on countries, communities, and people as a result of Earth-system change.

Interspecies justice and Earth-system stability are operationalised by assessing each biophysical domain to determine how to enable stability, uphold resilience, and ensure that ecological functions remain conducive for all life forms. By adopting an ecoregional scale target for largely intact natural ecosystem areas and sub-global targets for water, we ensure the protection of most species worldwide. However, even within safe and just ESBs, because we focus on significant, irreversible harm, many species and ecosystems can still be harmed under certain conditions; the definition does not imply that we protect all species and ecosystems and thus does not fully capture the meaning of interspecies justice.[56] This method corresponds with that used to identify safe ESBs.

We use the lens of intergenerational justice to assess whether an ESB (including those that reduce the risk of crossing tipping points) respects future generations, and acknowledge that past generations have already contributed to crossing critical boundaries. We also assess whether the safe ESBs meet the criteria for intragenerational justice, using three approaches. First, for each domain, we survey published literature that reports harmful effects to different places and vulnerable groups,

See **Online** for appendix

### *Panel 3*: Safe and just ESBs*

- Climate: a maximum of 1·0°C of global warming
- Biosphere:
  - Natural ecosystem area: >50–60% should be largely intact, depending on spatial distribution (upper end recommended)
  - Functional integrity: >20–25% of each km² should comprise natural or semi-natural vegetation
- Freshwater:
  - Surface water flow: <20% monthly flow alteration (aligned with WHO and UN Environment Programme quality standards)
  - Groundwater: annual drawdown from natural and anthropogenic factors does not exceed recharge (aligned with WHO and UN Environment Programme quality standards)
- Nutrients:
  - Nitrogen: surplus <57 (uncertainty range 34–74) Tg per year (total input <134 [85–170] Tg per year)
  - Phosphorus: surplus <4·5–9 (the ESB itself is the uncertainty range) Tg per year (mined input <16 [uncertainty range 8–17] Tg per year); aligned with local boundary to avoid eutrophication (<50–100 mg per m³)
- Aerosols and air pollution: annual mean interhemispheric aerosol optical depth difference <0·15 (aligned with an annual limit of 15 μg/m³ of particulate matter smaller than 2·5 μm in diameter).

Seven of the eight globally defined ESBs have already been crossed. At the local level, in more than 50% of land area, at least two local ESBs have been transgressed, with 86% of humans living in these areas.

ESBs=Earth-system boundaries. *ESBs were first presented in Rockström et al, 2023.[10]

and use expert elicitation within the Earth Commission. Rockström and colleagues found, for example, that for climate, the safe ESB of 1·5°C does not prevent widespread and significant harm to current generations, let alone future ones, and propose that the safe and just ESB should be 1°C.[10] Second, as appropriate, we complement the safe ESBs with international health standards for these domains that should be adhered to (eg, guidelines for drinking water quality) in order to avoid significant harm. Third, for each domain, we map the spatial distribution of the risk of harm, a function of the nature and degree of biophysical change (ie, hazard), the extent to which people are exposed to biophysical changes (ie, exposure), and vulnerability (ie, susceptibility and capacity to adapt). We map exposure to biophysical hazards based on population distributions to show where sub-global boundaries have already been transgressed (exposing people to harm) and the unequal distribution of exposure (appendix pp 11–12). We overlay poverty as a proxy for vulnerability to map the geography of injustice when exposed populations are also poor.

Our justice approach has several limitations. First, although staying within just ESBs could avoid harm to substantial proportions of the human population, it does not guarantee just outcomes, as noted in our discussion of each domain. Second, the high levels of aggregation and the use of poverty to indicate vulnerability overlook more detailed analyses of distributional justice in terms of which social subgroups (and other species) are most harmed and under what scenarios, as well as more complex drivers of vulnerability or responsibility for exposure and vulnerability. Third, we have not explored future scenarios in which social conditions have changed or the risk that mitigation policies could increase exposure and vulnerability for some people. We try to avoid a trade-off between interspecies, intergenerational, and intragenerational justice by calling for transformations that ensure human health and wellbeing while staying within a safe and just corridor.

Aligned with the SDGs of eradicating poverty, reducing inequality, and ensuring access to food, energy, water, and infrastructure for all people, we investigate the Earth-system implications of providing access to resources to those who do not have access as of 2018. We use two levels of just minimum access to key resources and services for water, food, energy, and infrastructure: basic dignity (level 1), and escape from poverty (level 2).[13] Informed by proposals such as the Decent Living Standards[73] rather than monetary measures of poverty, the basic dignity level is rooted in human rights,[74–78] including the rights to clean water, energy, food, and housing, and enables a dignified life beyond mere survival. Level 2 describes increased access to resources to enable activities considered necessary to break out of poverty and other deprivations,[79] and to potentially empower people to make use of their resources to achieve certain capabilities and thus ensure broader wellbeing.[80] In this Commission, we go beyond previous work that quantified the impact of providing minimum access to resources for those without access in 2018 to estimate the impacts in 2050. The technical methods have been previously described.[13]

Previous analyses have shown that seven of the eight globally defined safe and just ESBs have already been transgressed,[10] even though the minimum access to resources has not been met for billions of people. We conduct novel analyses to visualise a safe and just corridor in which the ceiling is the more stringent of the safe and just ESBs, and the base is defined as the impact on the Earth system if all humans consumed resources at level 2 of minimum access and no more (figure 4). These analyses involve the conversion of the safe and just ESBs to common units of impact on the Earth system (as per Rammelt and colleagues[13]) to visualise the base and ceiling of the corridor.

Our translation approach is based on literature reviews and expert elicitation. Key steps of translation include transcription, allocation, and adjustments underpinned by different sharing approaches and expressed with enacting metrics.[81] Our transformation narrative is based on an extensive literature review, expert elicitation, and our Earth-system justice framework. By expert elicitation, we mean the expert judgement of the Earth Commission and five working groups representing a wider community of social and natural scientists, including young scholars in the secretariat of the Earth Commission—more than 100 scholars in total.

## Part 2: Safe and just ESBs and the safe and just corridor

In this section, we present eight safe and just ESBs for five domains (panel 3). We analyse the Earth-system implications of meeting the minimum access to resource needs of people in 2018 and in 2050 (with some assumptions about changes in technology and redistribution). We also introduce an outlook for safe and just ESBs for some novel entities (panel 4).

### The biosphere

The biosphere has multiple dimensions, including evolutionary processes and innumerable ecological functions[94] that underpin life on Earth and contribute to social, cultural, and economic aspects of wellbeing.[95,96] Loss of biodiversity affects the natural world and human wellbeing, notably through the loss of nature's contributions to people (NCP), including pollination, soil fertility, and pest and disease control, all of which affect human health, healthy food production, food security, and livelihoods.[97] More than 75% of important food crops rely on animal pollination, and pollinators are crucial for healthy and varied diets and for biofuels, fibres, and construction materials.[98]

#### *Safe ESBs*

The biosphere is adaptive, serving as a stock and flow regulator for Earth-system processes such as carbon, water, and nutrient cycles. Changes in species' composition, distribution, and richness can affect local and global processes.[94] To ensure safe biosphere ESBs, it is necessary to secure largely intact natural ecosystems that assure Earth-system functions (eg, secure stocks and flows of carbon, water, and nutrients, and halt species extinction); to promote functional integrity of all landscapes and seascapes globally to secure local and global contributions to human wellbeing; and to ensure contributions to Earth-system functions through the provisioning of NCP, or meeting the requirements of interspecies justice.[99]

The biosphere has different facets,[100] each with different boundaries that can vary based on the specific characteristics of the local ecosystem. We capture the main components by identifying safe boundaries for two complementary and synthetic measures of biodiversity: the area of largely intact natural ecosystems, and the functional integrity of ecosystems heavily modified by human pressures.[10,101] Use of both of these measures ensures a minimum level of functional composition, diversity, and richness of ecological communities crucial for regulating nutrient cycles, water flows, and carbon stocks and flows on a global scale, and for supporting the provision of NCP, which underpins the wellbeing of local people and their quality of life.

For the area of natural ecosystems, we estimated the minimum global boundary based on experiments in conservation planning in the literature.[102,103] About 45–50% of the world's ice-free land surface is largely intact.[104,105] Our estimated safe ESB is that around 50–60% of global land surface should be in largely intact, natural condition to halt species extinction, secure biosphere contributions to climate regulation, and stabilise regional water cycles.[10] The amount of intact natural land as of 2018 was around

**Panel 4: Exploring novel entities for future analysis**

We acknowledge that there are other domains for which we have not quantified Earth-system boundaries but which we would like to explore in the future. For example, evidence on the diverse risk potentials of novel entities (eg, emerging pollutants and contaminants, radioactive waste, heavy metals, antibiotics, microplastics) for people (eg, effects on fertility, health, and food security) is increasing.[82–85]

Progress towards quantifications of the Earth-system boundaries for novel entities highlight the need for a differentiated approach to capture complexity and the absence of prehuman background levels.[82,86–88] Tracking trends on the release and production of novel entities (eg, production, volume, and emission or release quantities of chemicals and plastics, as well as different impacts) and establishing control variables indicates that humanity has crossed the novel entity boundary. The long-term effects of many novel entities could continue to pose a threat even if actions to control production and release were taken today.[87]

Knowledge gaps relating to the scale and scope of impacts of novel entities remain. Only a few thousand of the roughly 140 000 (and increasing) synthetic chemicals have been tested for toxic effects on other organisms,[84,87] and possible interactions across these entities are unknown.

Novel entities can harm human health through uptake via various channels (eg, water, air,[89] food, food packaging, cosmetics, clothing). For example, microplastics have been detected worldwide[90] and in human blood.[91] Microplastics and nanoplastics can alter the intestinal flora, potentially leading to diabetes, obesity, and chronic liver disease.[92] Water in plastic bottles often has higher concentrations of microplastics than processed tap water.[92] Antimicrobial-resistant bacteria have been detected in more than a quarter of the studied rivers, reflecting the pharmaceutical fingerprint of nearby populations.[93] These issues are closely linked to justice and access concerns relating to technology choice and management capacity, and economic means and information.

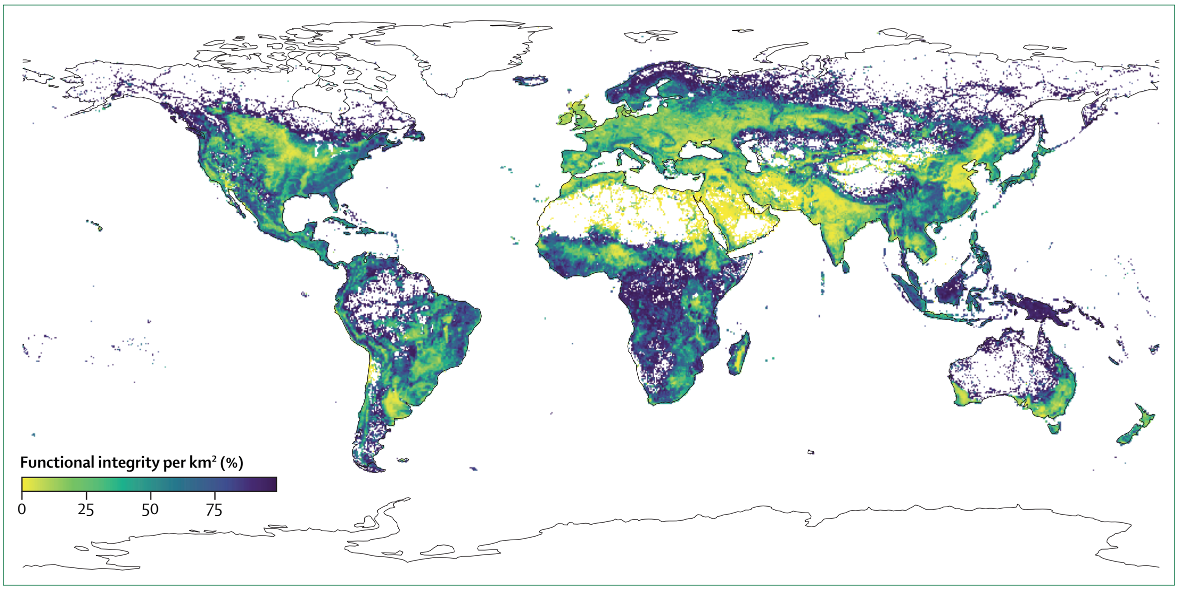

*Figure 5:* **Spatial distribution of biosphere functional integrity in working lands**
The map shows a proximate measure of the functional integrity of human-modified lands (agriculture, cities), indicating the proportion of natural land within 1 km² of each 10 m² pixel plotted. The lower the functional integrity, the lower the likelihood that nature's contribution to people (eg, pollination, pest and disease control, water-quality regulation, soil protection, natural hazards mitigation, and recreation) will be provided. The Earth-system boundary for functional integrity is 20–25%, a level at which many of nature's contributions to people are substantially diminished. Data source: Mohamed et al, 2024.[101] Areas in white were not assessed because of insufficient data, because of cloud coverage, or because of desert or ice cover.

15% below this ESB, but could be increased through restoring degraded ecosystems or previously converted ecosystems,[102,103,106] with conservation efforts distributed across all ecoregions. Strassburg and colleagues[102] estimated that restoration of 15% of converted lands in priority areas could avoid 60% of expected extinctions and sequester 299 gigatonnes of carbon dioxide. Our estimate for the safe ESB is higher than a previous calculation of the minimum area needed for conservation,[107] in which it was estimated that 44% of the terrestrial surface would need to be intact to safeguard species ranges. However, that estimate is focused only on species diversity and not the important Earth-system functions and functional contributions of the biosphere. Furthermore, these conservation areas are concentrated in some regions, resulting in critical shortages of NCP in other regions.

For the functional integrity of human-modified ecosystems, we systematically analysed six critical NCP at local scales to assess the minimum characteristics (area, quality, spatial configuration) required to avoid the loss of their contribution to human health and wellbeing (including pollination, pest and disease control, water-quality regulation, soil protection, natural hazards mitigation, and recreation). Our findings suggest that a safe boundary of at least 20–25% of natural or semi-natural habitat per km² in human-modified lands (ie, urban and agro-ecosystems) is needed to support both Earth-system NCP and local NCP, in addition to the functions provided by largely intact lands.[101] Our estimates are consistent with other evidence proposing that more than 20% of natural or semi-natural habitat is needed per km² globally to maintain NCP, especially those related to food production.[101,108–110] The exact area, quality, and spatial configuration required varies by contribution and location, and thus could not be estimated on a global scale, necessitating local translation, assessment of local context, demand for specific NCP, and application of best practices. The amounts of natural or semi-natural habitat needed could range from 6–15% in some landscapes (eg, riparian ecosystems, agricultural landscapes with high crop diversity) to 50% in others (eg, in sloping landscapes, or landscapes where erosion or natural hazards are frequent).[101] Many of the functional biological groups that provide local NCP are either non-mobile, or move very short distances (eg, pollinating insects and pest-regulating predators and parasitoids that move up to 2000 m), and thus NCP provisioning is driven by the spatial configuration of the habitat and its accessibility to beneficiaries.[101] Additionally, NCP are most used where humans are present, notably agricultural lands dependent on pollination and pest control, or urban ecosystems where recreational spaces support human physicial and mental health. We emphasise that the ESB of 20–25% natural or semi-natural habitats per km² is a boundary limit to ensure just NCP provision. 10% of natural or semi-natural habitat per km² is a sharper threshold, below which evidence suggests that many NCP would almost no longer be provided.[101]

Both biosphere boundaries are spatially defined and therefore require spatially differentiated responses (figure 5). Expansion of intact natural ecosystems could limit people's access to land for agriculture or other activities, but could simultaneously help people who are dependent on resources from natural areas.[111,112] Therefore, locations for restoration should be chosen within integrated land-use planning approaches to avoid trade-offs while optimising synergies. In human-modified lands, the functional integrity of ecosystems often determines peoples' access to locally constrained NCP. To identify where people have insufficient local access to NCP in human-modified ecosystems, we used spatially explicit estimates of the proportion of natural or semi-natural habitat in human-modified landscapes at scales of 1 km² and global gridded population models to estimate the number of people with insufficient access to local NCP.

### *Just ESBs*

Our Earth-system justice analysis of the safe boundary for natural ecosystem area suggests that adhering to it would reduce harm to other species and to future generations. However, distributional challenges would raise concerns from an intragenerational justice perspective. Protection and restoration of largely intact natural areas is often targeted at biodiversity-rich habitats located in low-income countries,[102] where vulnerable populations might reside with high dependence on biodiversity locally. More than 80% of global biodiversity is in the territories of Indigenous peoples.[113] Previous initiatives to reserve a certain proportion of the planet for nature were criticised for ignoring social issues and justice, notably the proposals to conserve half of the world's land and half of the oceans.[114,115] Scholars emphasise the potential risks associated with reserving a proportion of the world for non-human nature to human rights and food production, and the risk of increased land prices, land grabbing and displacement,[116] and related equity challenges[117] potentially affecting a billion people.[118] However, the continued loss of largely intact nature puts biodiversity and climate security at risk, with growing evidence that overconsumption of unhealthy diets is a greater risk to environmental security than lack of productive land is to food security.[119]

More than 3·2 billion people are affected by degraded lands[120] and could benefit from the restoration of ecosystem integrity. Billions of people rely on natural medicines, the availability of which is now threatened by biodiversity loss.[121] Biodiversity loss affects water quality, and loss of mangroves could expose hundreds of millions of people to floods and cyclones.[121] Such losses in combination with rising temperature increase human exposure to zoonotic pathogens[122,123] and increase the risk of new pandemics. Furthermore, decreases in the prevalence of infectious diseases globally could be slowed or reversed because of deforestation.[124,125] These risks underscore how biodiversity loss undermines progress towards many social Sustainable Development Goals (SDGs).[3]

Adherence to our safe ESB requires that 50–60% of terrestrial area should be left largely intact as natural land but with the caveat that this should be done through just transformations that avoid negative impacts on livelihoods. This proposal would require the area of largely intact natural land (as of 2020) to be expanded by about 15% through restoration. How this expansion would affect countries, communities, and people depends on land rights, the implementation of the boundary,[126] and how natural area is defined. People should not be excluded from largely intact natural ecosystem areas when it is possible to live with nature without destroying it—eg, various Indigenous peoples have often sustainably maintained largely intact areas.[127,128]

If, on average, 50–60% of the global land area should remain largely intact, to avoid an inequitable distribution of the responsibility,[10] the just boundary (ie, that which, if adhered to, would ensure no significant harm) needs to be at the upper end of this range, and the burden of action to restore largely intact land should be placed on those with the greatest responsibility for damaging biodiversity and the greatest capabilities, and based on inclusive conservation.[129] A 15% restoration is adequate if focused on the most biodiverse regions, where even a smaller percentage of restoration effort can yield substantial biodiversity benefits; however, these regions could have high opportunity costs because they might be valuable for other economic activities, such as agriculture or urban development. Therefore, restoration efforts are also needed in less biodiverse regions, where more restoration is necessary because such restoration is less efficient in terms of biodiversity benefits per unit of effort compared with the most biodiverse regions. Restoration efforts in less biodiverse regions will also ensure that wealthier regions contribute more to restoration efforts than poorer regions. Restoration areas need to be chosen carefully, and these decisions should account for the interests of the most vulnerable communities and densely populated areas where the risk of land conflict is high.[130]

The safe boundary for functional integrity contributes to interspecies justice through the high value of small patches and landscape elements for species conservation, but its exact contribution is uncertain and context dependent. This boundary targets intragenerational justice by ensuring universal access to NCP within a 1 km² spatial scale. It also enhances intergenerational justice by supporting agro-ecosystems and the functioning of urban systems, and by increasing ecosystem resilience against the effects of climate change on future NCP provisioning. Adherence to this ESB would reduce local food shortages, deaths caused by flooding and landslides, and agricultural runoff, which would in turn have beneficial effects on water quality, human health, and infrastructure. However, adherence to the ESB could also put a heavy burden on the local people responsible for

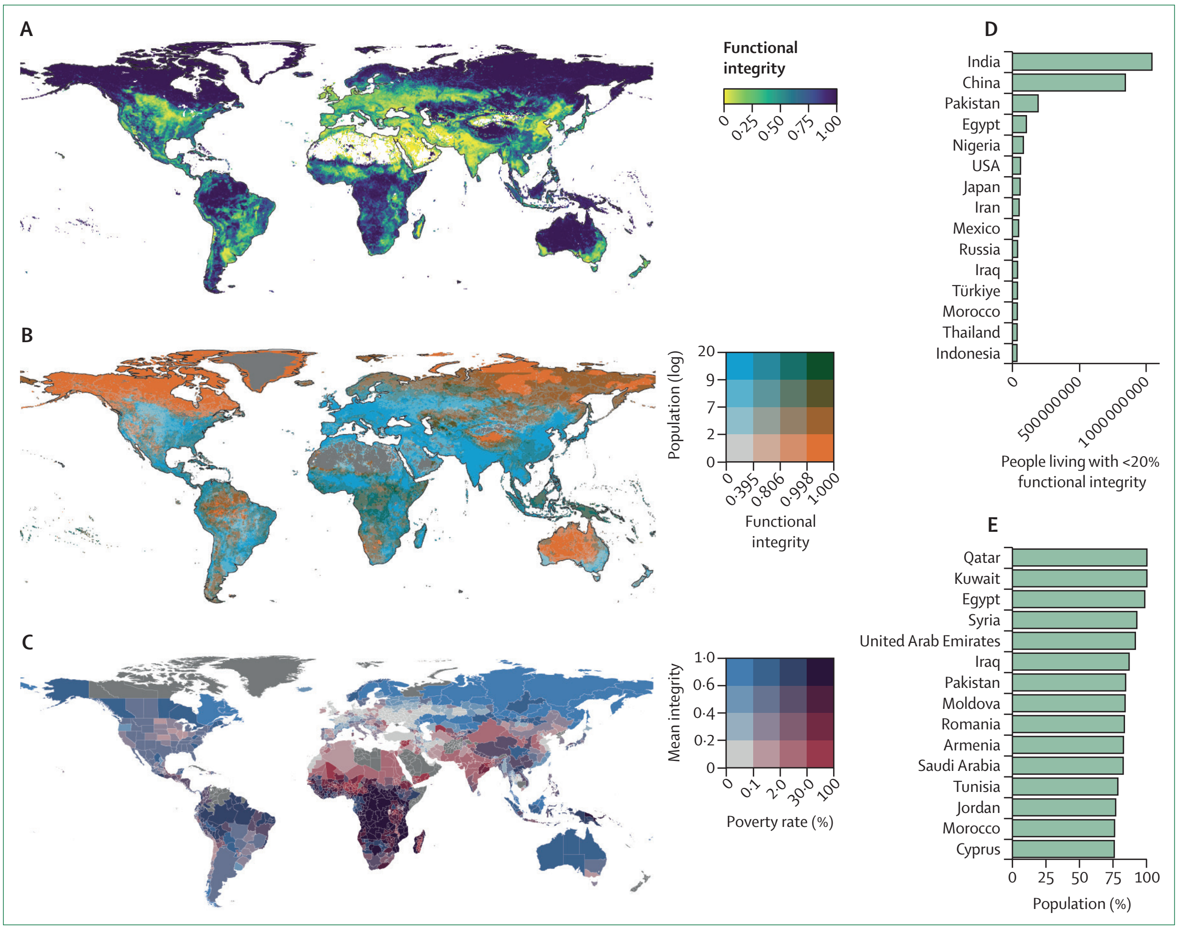

***Figure 6:*** **Exposure and vulnerability to loss of functional integrity**

(A) Biosphere functional integrity for terrestrial ecosystems combining natural and human-modified lands. Areas with <20–25% functional integrity are outside the Earth-system boundary.[100,101] (B) Plot of functional integrity with population (0·25° resolution) as a proxy of exposure to loss of nature's contribution to people. Each colour break represents the intersection of both distributions using quartiles. Values of population are log transformed. (C) Plot of functional integrity with poverty (a proxy of vulnerability). Poverty is measured as the proportion of people at the second level administrative unit who live under the US$1·90 poverty line as of 2018 (data source: World Bank 2021[131]). The proportions were calculated in a log-transformed population, with 0·1, 2·0, 30·0 reflecting the 25%, 50%, and 75% quantiles of the poverty distribution respectively. (D) The 15 countries with the highest absolute population living with <20% functional integrity. (E) The 15 countries with the largest relative population living with <20% functional integrity.

executing this goal, because ensuring functional integrity involves navigating complex ecological interactions and managing the direct impact of these interactions on local communities, while also addressing long-term sustainability challenges and balancing multiple environmental objectives. We propose that the just boundary for functional integrity is aligned with the safe boundary,[10] but warn against increasing the burden of action on poor and marginalised people.

There has been serious and accelerated loss of functional integrity across Europe, India, China, and the Americas over the past 50 years or so (figure 6A). Millions of people are exposed to this loss and associated impacts on NCP, such as pollination or watershed protection (figure 6B). In some cases, such losses are concentrated where poor people live (figure 6C). However, people far beyond the affected regions can also be harmed—for example, epidemics and loss of food security associated with loss of functional integrity in one region can exacerbate vulnerability in many other regions.[132]

There will be significant trade-offs regarding the current use of land and water in areas with low functional integrity that will require substantial transformations. Although wealthier areas have higher capacity to tackle the problem, a degraded biosphere disproportionately affects vulnerable people with low adaptive capacity,[111] people who consume directly from local ecosystems,[133] Indigenous people, and people who depend on natural medicines.[120] About 1·2 billion people, or 30% of the population across tropical countries, directly depend on NCP.[111] In such areas, meeting these stringent ESBs could benefit many people, but could also create injustice if people's needs for basic food, fuel, and infrastructure are not taken into account. Strategies to protect or restore ecosystems should account for justice concerns and people's wellbeing to minimise trade-offs between biodiversity conservation and the fulfilment of basic human needs.[126]

## Climate

Global warming threatens the stability of the Earth system and the lives and livelihoods of present and future generations.[3,134] Extreme temperatures cause millions of deaths every year, and heat-related mortality is rising.[135] Droughts and floods affect crop production and drinking water worldwide, and livelihoods and food security have been lost in coastal communities as a result of warming oceans and loss of coral reefs. Vector-borne and water-borne diseases, such as dengue fever, malaria, and cholera, are a particular risk for poor and marginalised people and those in places with weak health systems.[3] WHO estimates that climate change will cause 250 000 additional deaths every year between 2030 and 2050[134] due to malnutrition, malaria, diarrhoea, and heat stress. These estimates might be underestimates. Springmann and colleagues project that there could be as many as 529 000 premature adult deaths by 2050 due to food shortages alone.[136] Increasing carbon dioxide concentrations could reduce the nutritional value of cereal crops and protein availability by 20% during the coming century.[137,138]

### *Safe ESB*

Anthropogenic emission of greenhouse gases (predominantly carbon dioxide and methane) has caused global surface temperatures to increase by at least 1·1°C relative to pre-industrial global mean temperatures.[139] This increase is already having observable negative effects on people and ecosystems, with much more severe impacts likely to manifest with increases of 2°C or higher.[3] How much global warming and climate change affect current and future generations depends on choices made within the coming decades.[140] To avoid the potential negative impacts, the 2015 Paris Agreement set out to limit global warming to "well below 2°C", while aiming for warming of no more than 1·5°C.[141] However, current policies are projected to lead to warming of around 2·6°C by 2100, and even ambitious net-zero targets, if actually achieved, are likely to lead to around 1·9–2·0°C of warming by 2100.[142] Recent extreme weather, such as 2023's record-breaking temperatures across multiple regions, the South Asian heatwave of 2022, and the North American heatwaves in 2021, also call into question whether current limits are in fact safe.

The Earth Commission set the safe climate ESB at 1·5°C (1–2°C) of warming but suggested that the just limit should be lower: 1°C.[10] The safe limit was drawn from an analysis[16] based primarily on the notion that the likelihood of passing multiple climate tipping points would become moderate with 1°C of warming and high with 1·5°C warming; the analysis also incorporated Earth-system impacts unrelated to tipping points that affect biosphere functioning (eg, some areas that absorb some human carbon dioxide emissions—natural carbon sinks—absorb less when warming is higher than 1°C and are projected to start emitting carbon dioxide when warming increases beyond 1·5°C),[143–148] the average temperature range of the Holocene (with temperatures not increasing above 0·5–1°C relative to the pre-industrial period during the past 12 000 years or so), and the temperature range of previous interglacial periods (<1·5–2·1°C).[149–153] The safe ESB also aligns with the IPCC's reasons for concern—which include increasing risks to endangered species and unique systems, damages from extreme climate events, effects that fall most heavily on low-income countries and the poor within countries, global aggregate impacts, and large-scale high-impact events—several of which become high risk or very high risk beyond 1·5°C.[140,154] By integrating this state-of-the art knowledge on climate tipping elements with the IPCC assessments and incorporating the role of the cryosphere in Earth-system stability, the resulting ESBs closely reflect previous assessments of climate risk, with a boundary of a 1·5°C increase purported to be substantially safer for the biosphere (eg, avoiding extinctions) than a 2°C increase,[143] and the range of 1°C–2°C reflecting climate limits proposed since 1990.[155]

Figure 7 shows the spatial distribution of key climate tipping elements proposed by Armstrong McKay and colleagues.[16] Although some of the impacts of passing climate tipping points would be global (eg, rising sea levels resulting from the collapse of ice sheets, carbon release from forest dieback or permafrost thaw leading to amplified global warming), others would be felt primarily locally (eg, coral ecosystem collapse, extra-polar glacier loss reducing water supplies, loss of Amazon biocultural diversity).

The climate system also has considerable inertia that varies among the subsystems, with the atmosphere exhibiting the least and the cryosphere the most.[156] This characteristic of the climate system means that the greenhouse gas emissions that are driving climate change will continue to drive changes in the future on long time scales, even if emissions are substantially reduced.[156] Adding further to the complexity is the strong spatial heterogeneity within these climate subsystems and their sub-components globally, which mean that global sums and averages of realised and committed changes can convey an exaggerated sense of security. For example, the planet does not warm uniformly, meaning that a global mean annual temperature increase of 1·5°C will result in larger temperature increases in polar regions and on land, with subsequent impacts on the biosphere. Committed change is of particular importance when considering climate tipping elements and their effective irreversibility. With

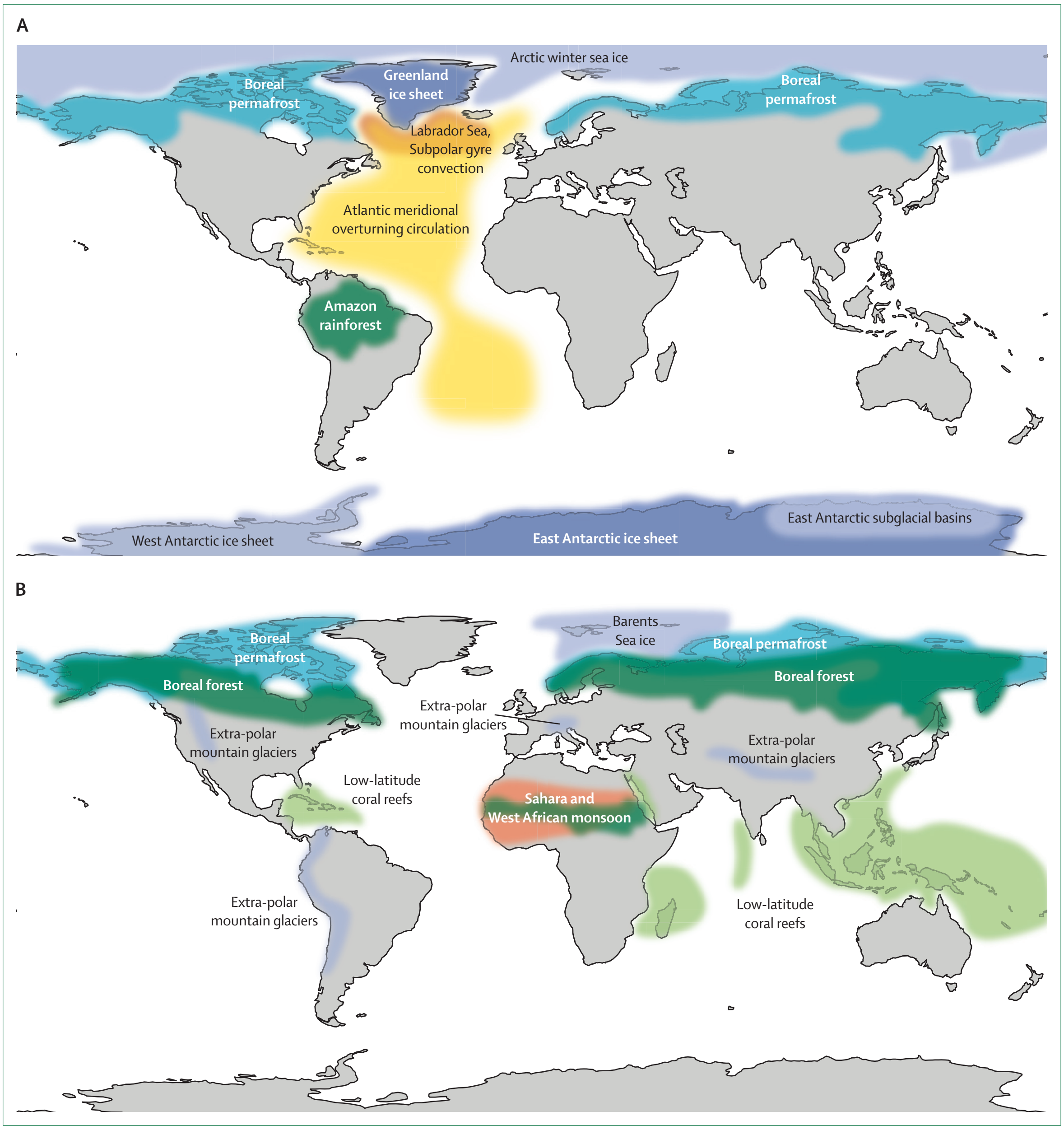

***Figure 7:*** **Map showing global core (A) and regional impact (B) climate tipping elements.**
Passing the tipping point of any element would lock-in negative ecological and societal impacts in the vicinity of the element in both (A) and (B), as well as on a global scale for those in (A). Reproduced from Armstrong McKay et al, 2022,[16] with permission from the American Association for the Advancement of Science.

the 2024 level of mean warming (around 1·2°C), some tipping point temperature thresholds could be breached, as is shown by examples of major long-term committed changes in ice sheets and the terrestrial biosphere from previous emissions (Winkelmann et al, unpublished).

Figure 8 shows the difference in realised versus committed changes for land carbon and ice sheets for a fixed global warming level under a high emissions scenario in 2100 (specifically Representative Concentration Pathway [RCP] 8.5, a high-emissions climate-change scenario for future greenhouse gas concentrations used by the IPCC, which, in this experimental set-up, corresponded to an increase of around 4·7°C in global mean temperature compared with that in 1850–1900). Greenland and west Antarctica are committed to far more ice loss than is predicted to occur by 2100 (figure 8; with subsequent implications for sea-level rise), and similarly local land carbon losses and gains become far more pronounced (Winkelmann et al, unpublished). Such committed changes in land carbon suggest that major changes in ecosystem distributions and processes might unfold with

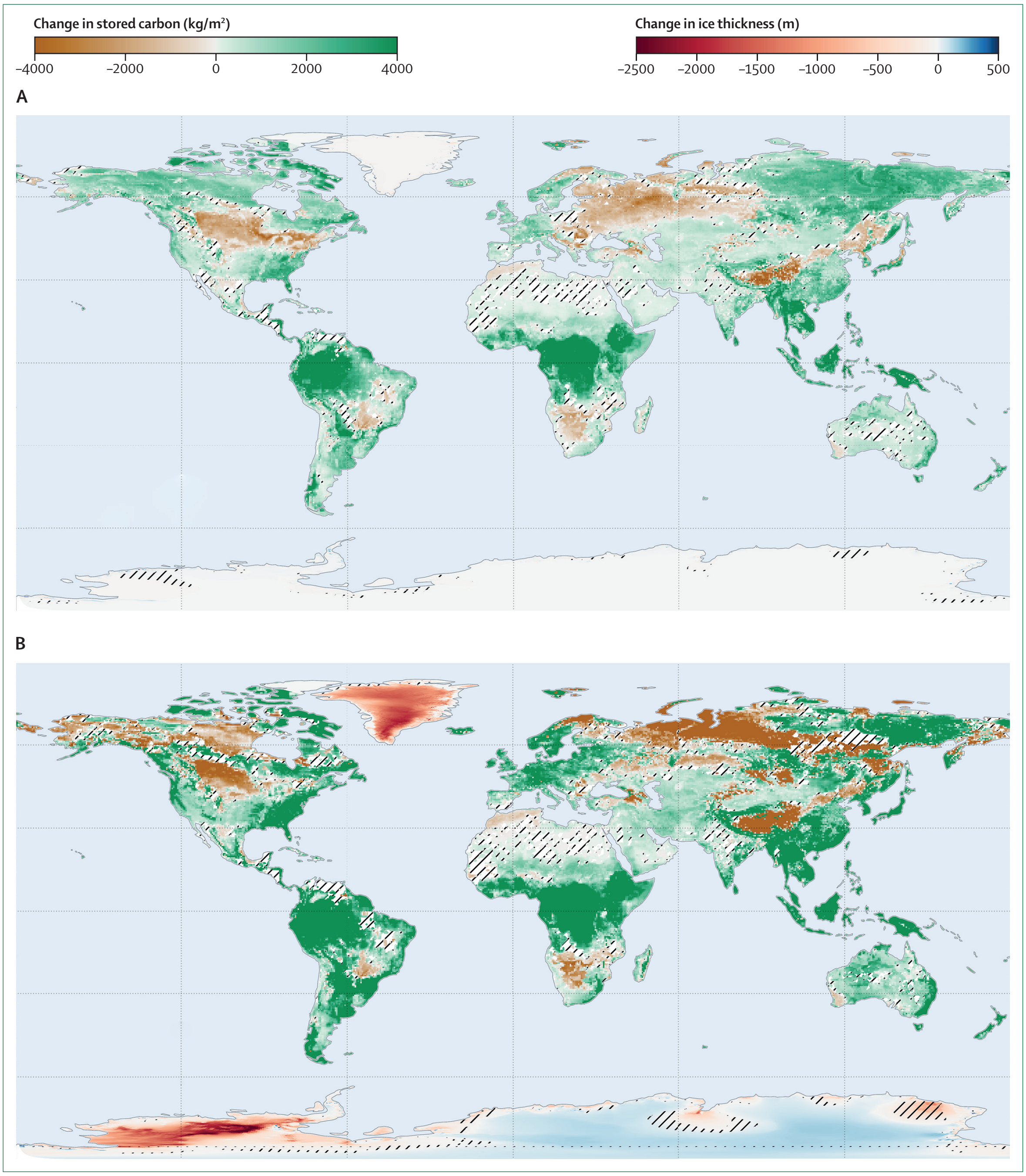

***Figure 8:* Directly realised (A) and potentially committed (B) in change of land carbon and ice thickness under RCP8.5 in 2100**
RCP 8.5 is the Intergovernmental Panel on Climate Change representative concentration pathway in which emissions continue to rise through the 21st century. A global vegetation model and an ice sheet model were used for both (A) and (B); hatches represent areas where different simulations disagree qualitatively with the mean sign of change. Directly realised change refers to change in land carbon and ice thickness between 2020 and 2100. Committed change describes the change of land carbon and ice thickness between 2020 and 2100 with long-term equilibrium of the climate (ie, a constant climate and atmospheric carbon dioxide commitment; appendix p 12). Adapted from Rockström et al, 2023.[10]

substantial time lags. Furthermore, simulated land-carbon gains (Winkelmann et al, unpublished) hinge upon central assumptions of land-surface models (standalone or employed in Earth-system models), notably the strength of future carbon dioxide fertilisation of plants. By incorporating the latest data on regional and global land carbon sink saturation,[146,157–160] we found that constraining carbon dioxide fertilisation rates to 2020 rates would lead to the global land turning from a carbon sink to a carbon source within the next 10–20 years, with substantial

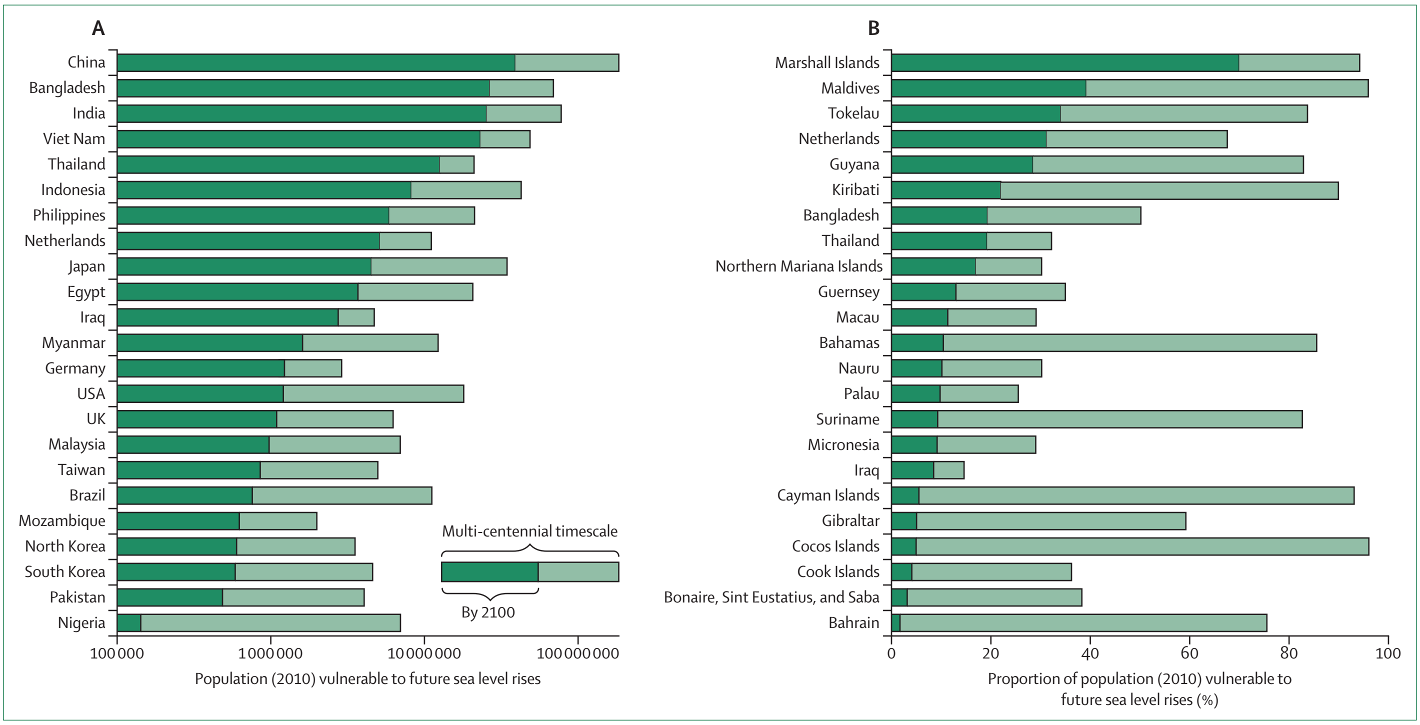

***Figure 9:*** **Total population (A) and relative population (B) living on land exposed to potential future sea level rises**
The figure is based on 2010 populations and a temperature stabilisation of 2°C by 2100 for the top affected countries in (A). Both the potential impact by 2100 and the additional committed impact on a multi-century time scale are graphed. Adapted from Strauss et al, 2021.[161]

carbon release projected from almost the entire global land surface (figure 8). These projections underline the need for stringent ESBs that account for the increased risks to intergenerational equity resulting from committed changes (figures 8, 9). Passing climate tipping points will similarly lock in many negative impacts over long timescales, underlining the importance of the safe climate ESB.

### *Just ESB*

The proposed safe ESB for climate change of no more than 1·5°C of warming meets the criteria for intraspecies justice in that, if adhered to, it would prevent climate tipping points from being passed and avoid many committed changes that could affect many habitats and people, and could also minimise degradation and vulnerability of other domains (eg, biosphere exposure to droughts, and water-resource constraints), helping advance interspecies justice. However, many species have already been harmed in terms of habitat loss with less than 1°C of warming.[154]

The safe 1·5°C ESB for climate does not address intergenerational justice. With a global temperature rise of 1·0°C, the committed rise in sea levels threatens places home to hundreds of millions of people, and 565 million people are exposed to at least 1 day a year with wet bulb temperatures (a measure of heat stress combining temperature and humidity) greater than 32°C (figure 9). The safe working time for outdoor activities declines substantially with wet bulb temperatures of greater than 32°C,[162] while 35°C represents a limit of human physiological adaptability (although this limit could be several degrees lower).[163,164]

The risks posed by rising sea levels particularly affect populations living along low-lying coastal areas, island nations, coastal cities, and regions where poor people live in the lowest areas and might not receive storm warnings. Exposure within countries varies greatly, with low islands facing saltwater intrusion and storm damage, whereas Arctic Indigenous communities face existential risk to their lands, cultures and wellbeing from ice loss, permafrost melting, and rising sea levels.[3] Vulnerability to rising sea levels can be reduced through warning systems, social support, and appropriate infrastructure, but there are limits to adaptation.

Adherence to the safe climate ESB would also not provide intragenerational justice: 100 million people are already exposed to heat stress with global warming of 1·2°C—largely as a result of increases in wet bulb temperatures, especially in large cities where urban heat islands amplify exposure, and for people who cannot afford cooling and shade, lack access to water, are elderly or ill, or work outside.[3,165] We thus set the just ESB at 1°C of warming or less, recognising that even at this level, hundreds of millions of people are negatively affected.[154] Additionally, the risk of several harm-related IPCC reasons for concern (eg, unique threatened systems including Arctic Indigenous communities,

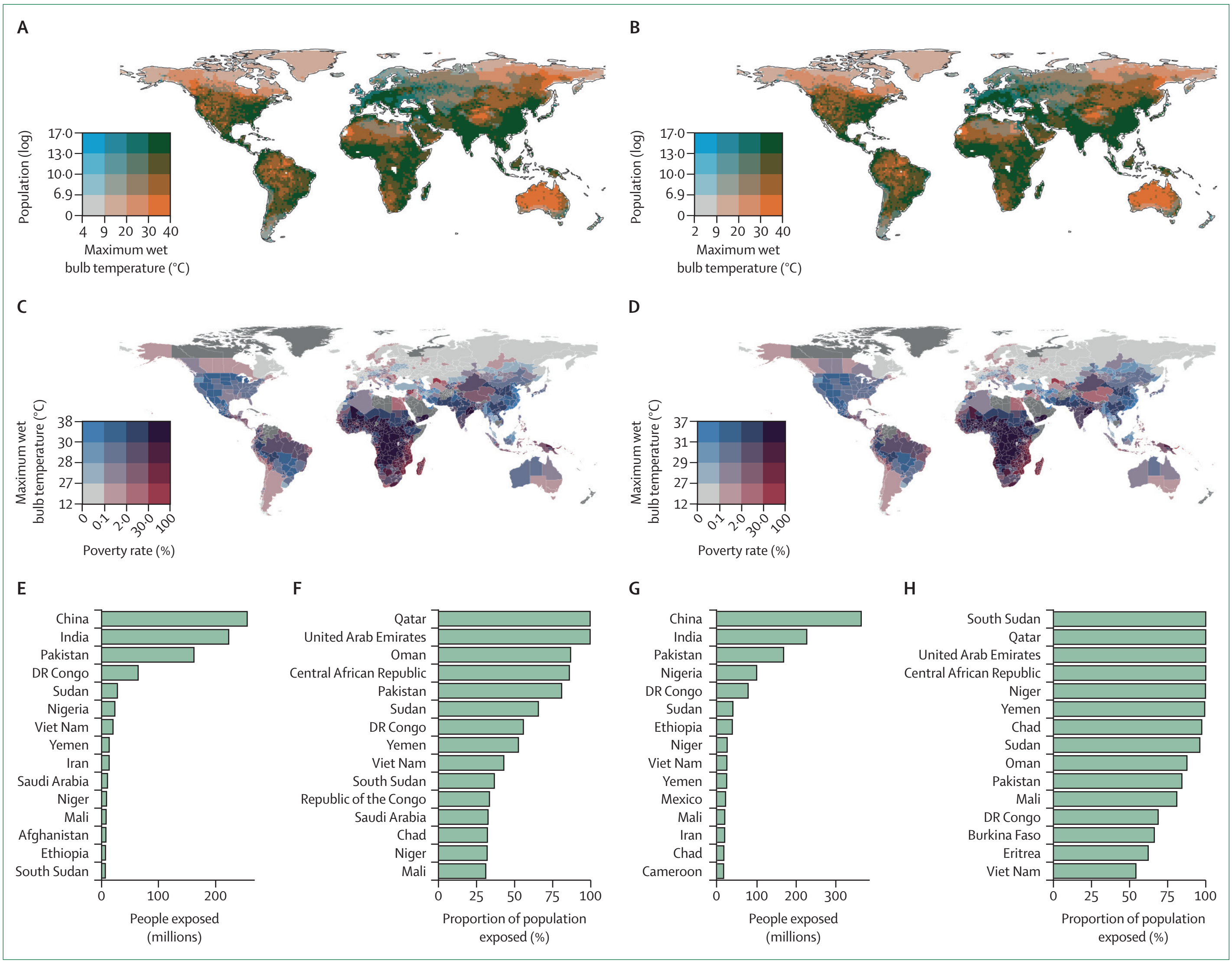

***Figure 10:*** **Distribution of harm from wet bulb temperatures**

Scenarios of exposure to the maximum wet bulb temperature in a 1·2°C world (A) and 2°C world (B), with exposure approximated as the number of people living in countries affected by different levels of temperature. In (C) and (D) exposure is plotted against the proportion of people living in poverty (ie, below the US$1·90 poverty line as of 2018 [data source: World Bank 2021]),[131] with poverty as a proxy of vulnerability. In (A), (B), (C), and (D), each colour break represents the intersection of both distributions using quartiles. (E) and (F) graph the countries with the highest total and relative population affected by high wet-bulb temperatures in a 1·2°C world, and (G) and (H) graph the countries with the highest total and relative population affected by high wet-bulb temperatures in a 2°C world.

extreme events, uneven impacts on vulnerable communities, aggregate economic impacts) coming to pass becomes moderate or high with global warming within the 1·0–1·5°C range.[140,154]

We mapped the spatial distribution of harm by using rises in sea levels and extreme temperatures (both wet bulb temperatures and mean annual temperature [figures 10, 11]). Previous analyses made efforts to link future rises in sea levels to end-of-century temperature stabilisation targets,[153,161,166] inferring impacts on decadal to multi-centennial timescales by taking into account committed change. A consistent way to illustrate the impact on populations at these timescales is to quantify the number of people inhabiting land today that will be exposed to inundation in the future. If populations (as of 2010) were exposed to the impact of rising sea levels and its distribution across the most affected countries under a 2°C temperature stabilisation target in 2100, in absolute and relative terms, China, Bangladesh, India, and Viet Nam would have the highest number of people exposed to rising sea levels (figure 9), with coastal impacts having wider implications for economies. Figure 9B shows the projected distribution in 2100 of populations potentially affected by rising sea levels with global warming of 2°C. The Marshall Islands, the Maldives, Tuvalu, the Netherlands, and Guyana are

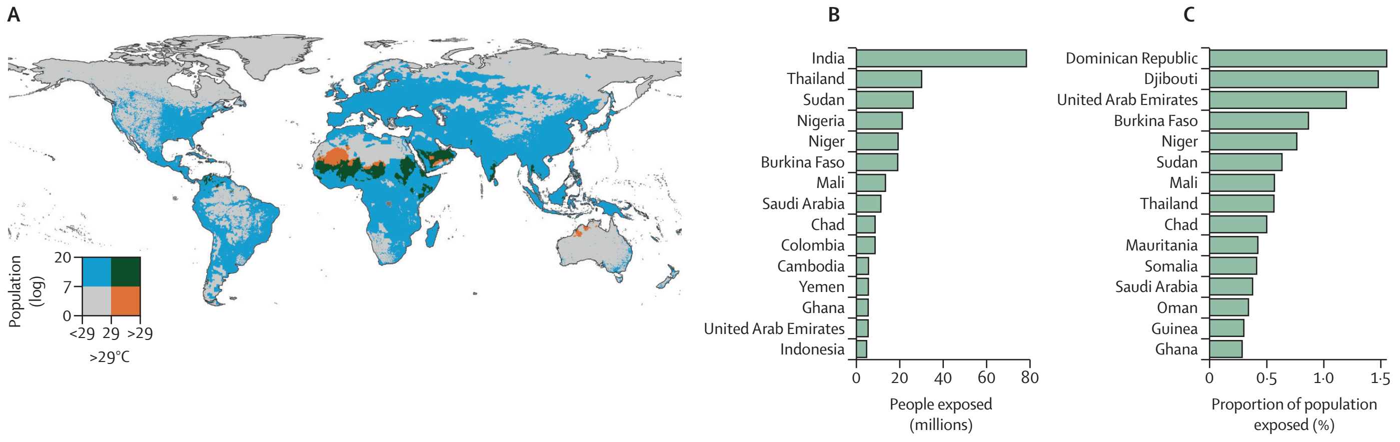

***Figure 11:*** **Spatial distribution of harm from mean annual temperature >29°C in a 1·5°C world (A) and countries with the highest absolute population (B) and relative population (C) exposed to these mean annual temperatures**

five countries with much of their territory exposed to rising sea levels. Over the next 200–2000 years, high proportions of the populations of the Bahamas, Cocos (Keeling) Islands, and Suriname will be affected (assuming the 2010 population).

Many regions are already facing extreme temperatures.[3] Figure 10 shows maximum wet bulb temperatures for a scenario with 1·2°C and 2°C warming. The human climate niche[167] describes the relationship between mean annual temperature, which has varied little for thousands of years, and relative human population density. For most of human history, human population density has been greatest in a rather narrow part of the available climate space in which mean annual temperature is roughly between 11°C and 15°C.[167] Climate and demographic change can increasingly expose people to temperatures outside this human climate niche. The simplest way to quantify this increasing exposure to conditions outside of the niche is to assess who would be exposed to unprecedented mean annual temperatures higher than 29°C (figure 11). In absolute numbers, India will have the highest number of people exposed to mean annual temperatures higher than 29°C if global temperatures warm by 1·5°C. South Asia, southeast Asia, west Africa, and the Arabian Peninsula would have large areas of land with mean annual temperatures exceeding 29°C. Several western African countries (eg, Burkina Faso) could find most of their territory being pushed outside the human climate niche.[168] Carbon budget estimates published in 2020 suggested that the most industrialised countries are responsible for 92% of global carbon dioxide emissions whereas the least industrialised countries are responsible for a much smaller fraction.[169] These quantifications exemplify the unequal share of responsibility in terms of causing global warming—and, by extension responsibility for solving it—with implications for intergenerational and intragenerational justice.

## Nutrient cycles

Nitrogen and phosphorus are essential macronutrients for plants—and thus for food production. Excess nutrient inputs and limited waste recycling result in substantial negative effects on the health of people and ecosystems. Many regions in Europe, North America, and Asia are well beyond proposed safe limits, while many regions in low-income and middle-income countries (LMICs) do not have sufficient fertiliser to ensure that food production meets people's needs.

### *Safe ESB for nitrogen*

Nitrogen is essential for crop production. Excess input not taken up by crops (ie, nitrogen surplus) can pollute terrestrial ecosystems, freshwater, groundwater, and drinking water via eutrophication, leading to substantial environmental damage.[170–174] Agriculture is the primary source of freshwater nitrogen pollution (accounting for around 75%), followed by domestic sources including sewage (23%) and industrial sources (2%).[175] In the ocean, excess nitrogen has led to a more than nine-times increase in hypoxic coastal sites since 1950, with complex effects on fisheries.[176]

To avoid significant harm to ecosystems and people, we set a global safe nitrogen ESB of 61 TgN per year of agricultural surplus from all sources (corresponding to total nitrogen inputs of 143 TgN per year at current nitrogen use efficiencies).[10] This safe ESB was based on an analysis published after the early planetary boundary quantifications,[7,9,177] in which regional environmental thresholds for two environmental systems (nitrogen runoff to surface water of around 2·5 mg nitrogen per L, and nitrogen emissions and deposition to terrestrial ecosystems of 5–20 kg nitrogen per hectare per year, depending on biome) were identified and associated critical losses, surpluses, and inputs were calculated regionally before aggregation to a global value.[172–174]

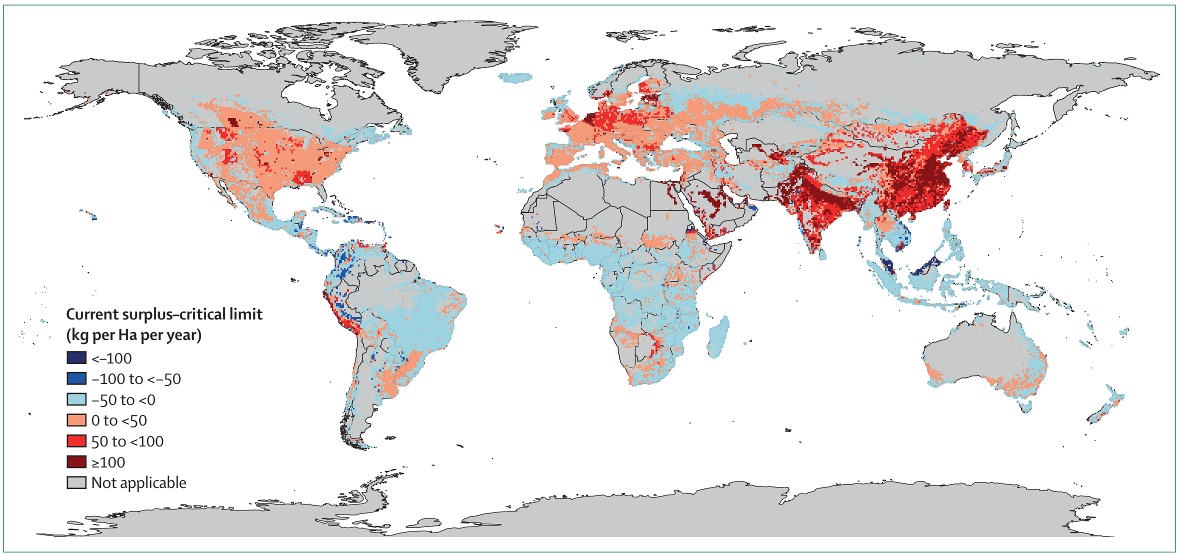

***Figure 12:* Map depicting the spatial variation in excess nitrogen surplus**
Nitrogen surplus is calculated with respect to nitrogen runoff to surface water, emissions, and deposition to terrestrial ecosystems, and nitrate leaching to groundwater. Nitrogen surplus is used as a proxy for potential harm caused by nitrogen pollution. Data for current nitrogen surplus on agricultural land (ie, arable and intensively managed grassland; measured in kg per Ha per year) are from the IMAGE model.[183] For each grid cell, the critical nitrogen surplus (from Schulte-Uebbing et al, 2022)[172] was subtracted from the current (2010) nitrogen surplus.

### *Just ESB for nitrogen*

The safe ESB for nitrogen seeks to reduce environmental degradation and effects on human wellbeing as a result of loss of ecosystem services (eg, fisheries). Our justice analysis suggests that the adherence to the safe nitrogen ESB could contribute to achieving interspecies justice by limiting ecosystem degradation of surface water and terrestrial ecosystems. However, as well as avoiding future tipping points, intergenerational and intragenerational justice require active restoration of already degraded ecosystems caused by past nitrogen pollution.

Nitrogen pollution also directly harms human health. Exposure to high concentrations of nitrates and nitrite in drinking water—which some of the world's most vulnerable populations have to deal with[178]—can cause infant methaemoglobinaemia, and is connected to adverse reproductive effects, colorectal cancer, and thyroid disease.[179] Excess agricultural nitrogen usage from manure and synthetic fertilisers leads to emissions of nitrogen oxides, and nitrogen dioxide pollution from all sources is linked with around 4 million new cases of paediatric asthma a year.[180] Fine particulate matter with a diameter of less than 2·5 μm ($PM_{2\cdot5}$) of agricultural origin, largely derived from ammonia, contributes roughly 20% of the approximately 3·3 million deaths per year associated with $PM_{2\cdot5}$.[181]

The safe ESB thus needs to be complemented with locally applicable health standards for nitrogen to set the just ESB. For water, we used the threshold from WHO's standards for drinking water quality of 50 mg nitrate per L (ie, equivalent to 11·3 mg nitrogen per L).[182] When applied to nitrate leaching to groundwater as a third environmental system threshold, this globally amounts to a safe surplus limit of 117 TgN per year, but in surface water it is less stringent than the safe threshold of roughly 2·5 mg nitrogen per L.[172–174] Incorporation of this standard for groundwater would reduce the sub-global critical nitrogen surplus in some regions (figure 12) and slightly lower the global safe and just ESB to 57 TgN per year (134 TgN per year in total inputs).[10,172] Local standards for nitrogen with regard to air quality are not directly included in our analysis of safe and just ESBs for nitrogen but are incorporated in the proposed just ESB for air pollution (discussed later in this Part), in which concentrations of $PM_{2\cdot5}$ are used as a comprehensive indicator.

Figure 12 shows the spatial variation in where estimated critical nitrogen surplus is exceeded on agricultural lands as of 2010.[172] We use these data as a proxy for the potential harm caused by nitrogen pollution, because, to our knowledge, global limits for the direct and indirect effects of nitrogen pollution on human health and wellbeing have not yet been sufficiently quantified. Excess nitrogen surplus is highest in China, south and west Asia, Europe, and North America, and mostly associated with intensive agriculture, whereas concentrations of nitrogen are below the critical limit across most of sub-Saharan Africa, Latin America, and southeast Asia (figure 12), where farmers tend to have insufficient access to fertilisers.

Figure 13 depicts the distribution of nitrogen pollution impacts as of 2010 relative to population distribution and poverty (as a proxy for vulnerability to harm from exposure to nitrogen pollution). This figure shows exposure to local nitrogen pollution only. It does

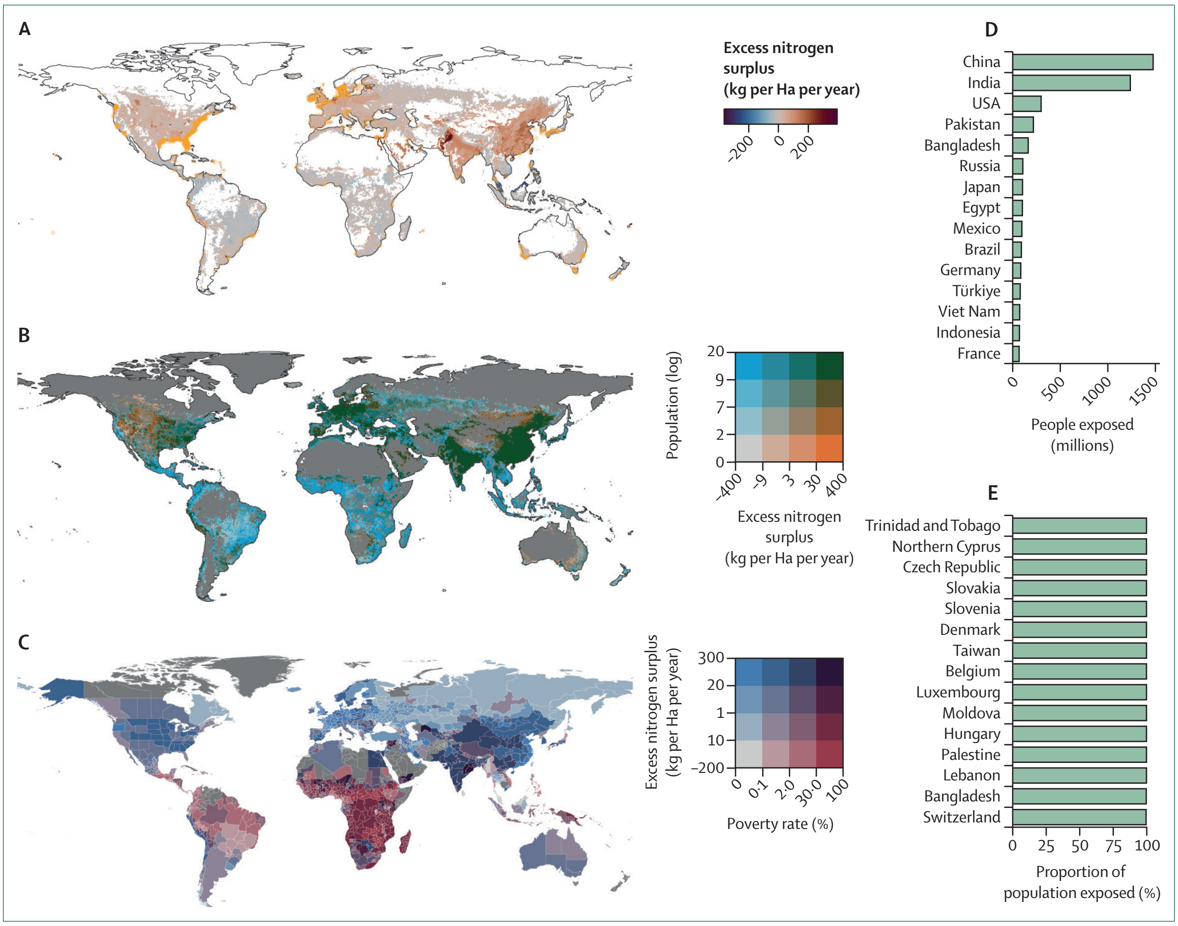

***Figure 13:*** **Global distribution of nitrogen pollution**

(A) Agricultural nitrogen surplus relative to the critical nitrogen surplus limit (2010)—a proxy for where nitrogen impacts are most felt. Areas of coastal eutrophication and hypoxia are represented by orange dots.[184] (B) Excess nitrogen surplus plotted against subnational population data. Each colour break represents the intersection of both distributions using quartiles; the middle columns indicate current nitrogen surpluses just above and below the critical N surplus limit. (C) Excess nitrogen surplus plotted against the proportion of people (on a subnational level) living in poverty (ie, below the US$1·90 poverty line as of 2018 [data source: World Bank 2021]),[131] with poverty as a proxy of vulnerability. Each colour break represents the intersection of both distributions using quartiles. Each colour break represents the intersection of both distributions using quartile. (D) The ten territories with the highest absolute population exposed to excess nitrogen surplus. (E) The ten countries and regions with the highest relative population exposed to excess nitrogen surplus.

not take into account how pollution also causes harm when transported downstream into shared lakes and oceans or downwind, and thus underestimates true vulnerability to nitrogen pollution. Neither does figure 13 take into account access to nitrogen fertilisers. Unsafe nitrogen surpluses coincide with high population exposure in China, South Asia, eastern USA, and Europe, and with increased poverty in South Asia, parts of China, and hotspots in central and west Asia. By contrast, areas where nitrogen concentrations are within safe limits and so where nitrogen fertiliser usage could increase include areas of poverty across much of sub-Saharan Africa, northern Latin America, and southeast Asia.

Although fertiliser overuse causes interspecies, intragenerational, and intergenerational harm, the biggest challenge related to nutrients and human health is insufficient access to nutrients needed for food security in many regions. For example, much of sub-Saharan Africa does not have access to sufficient and affordable fertilisers to maximise potential agricultural output, contributing to a yield gap.[185,186] Intragenerational justice requires more equitable access to nutrients to close large yield gaps in LMICs and to avoid the offshoring of nutrient depletion or pollution from wealthier countries via trade. Production of ammonia for synthetic nitrogen fertilisers is heavily dependent on fossil fuels, and is responsible for roughly 2% of global greenhouse gas emissions.[187] Minimising the use of synthetic nitrogen fertiliser could therefore contribute to intergenerational justice by reducing long-term climate impacts.

Minimising trade-offs while addressing justice issues will require better global nitrogen management[188] that builds on improved use and regenerative nutrient-conserving practices, ensures equitable access, and recycles nutrients. Nutrient pollution is often transnational

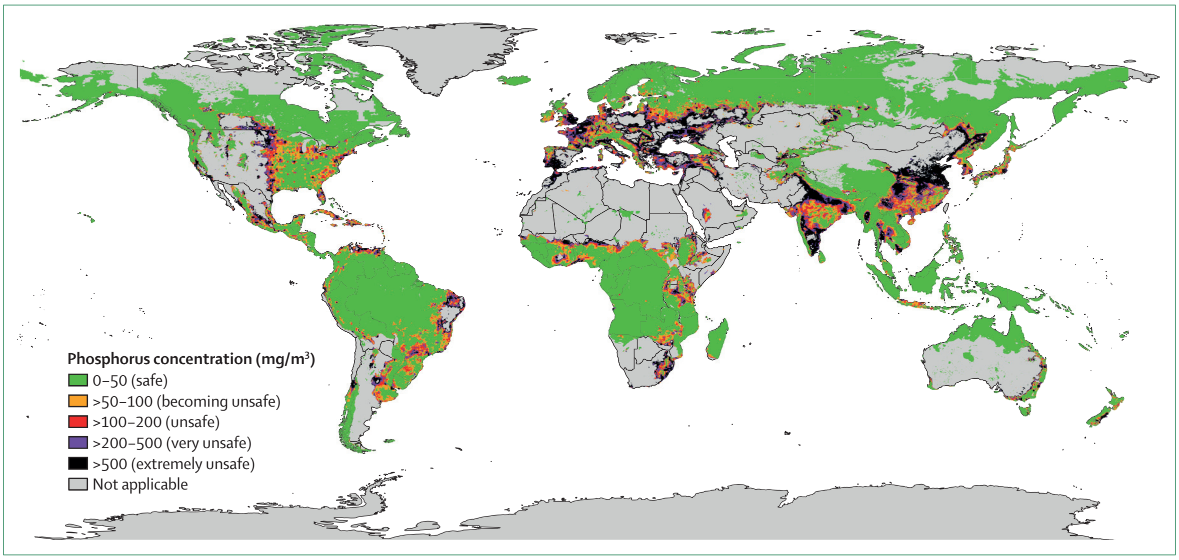

***Figure 14:* Global anthropogenic phosphorus concentrations in surface water from agriculture, industrial, and domestic sources in 2002–10**
We use phosphorus concentrations in surface water as a proxy for potential indirect harm caused by phosphorus pollution. Phosphorus data are from Mekonnen and Hoekstra, 2018,[194] and runoff data from Wisser et al, 2010,[201] and Fekete et al, 2001.[202] Areas with runoff of less than 5 mm per year and phosphorus concentrations higher than 10 g per $m^3$ have been masked to remove anomalous values in low-flow regions.

(eg, atmospheric ammonia deposition, eutrophication of shared rivers, coastal and open ocean hypoxia), and thus effective international governance will be needed.

### *Safe ESB for phosphorus*

Phosphorus is also an essential element for agriculture. Similar to nitrogen, excess phosphorus results in pollution, but unlike nitrogen, surplus P can accumulate by sorbing to soil and sediment particles.[189,190] Sorbing can limit fertiliser effectiveness in phosphorus-limited soils (because the phosphorus is sorbed instead of reaching crops), meaning more fertiliser is required.[191,192] The fraction of surplus phosphorus entering freshwaters via runoff or soil erosion is a key driver of freshwater eutrophication (along with nitrogen), and phosphorus build-up in waterway sediments prevents recovery through long-term phosphorus leaching.[193,194] Although nitrogen has a greater role in coastal hypoxia, in the longer-term excess phosphorus concentrations could result in global ocean anoxia.[195] Restricted access to phosphorus fertilisers causes yield gaps in many regions.

We suggest a global safe ESB for surplus soil phosphorus of 4·5–9·0 TgP per year (corresponding to 8–17 TgP per year of total input).[10] This ESB was based on literature[193,194,196,197] in which the phosphorus planetary boundary is quantified by directly calculating critical inputs, surpluses, and losses at a global scale (using generic phosphorus concentration thresholds in runoff to freshwater of 50–100 mg/$m^3$, which we use as our sub-global safe boundaries for phosphorus).

### *Just ESB for phosphorus*

The safe ESB for phosphorus would meet the criteria for interspecies and intergenerational justice, although some species would be locally harmed by phosphorus pollution. However, global phosphorus use exceeds the safe ESB and so threatens intragenerational justice, with phosphate mining harming local communities.[198–200] Although phosphorus has few direct effects on human health, algal blooms caused by eutrophication can produce harmful toxins that pose risks especially to children and animals and that cause damage to fisheries, thereby undermining food security.[193,194] We therefore align the just ESB for phosphorus with the safe ESB in terms of phosphorus quantities, supplemented by local health standards for water quality where necessary.

Figure 14 shows anthropogenic phosphorus concentration in surface water runoff as a proxy for potential harm from phosphorus pollution. Phosphorus pollution is concentrated in east and south Asia, Europe, and North America, with additional hotspots in south-east Asia, southern Africa, and South America. Domestic sources, especially sewage (ultimately derived from agricultural phosphorus inputs via food consumption) account for approximately 54% of freshwater phosphorus pollution globally, with the rest contributed by agriculture (~38%) and industrial sources (~8%).[194] However, these data mask substantial spatial heterogeneity—eg, sewage contributes more than 70% of phosphorus pollution in the Ganges river basin, including parts of Bangladesh, China, India, and Nepal, and agriculture contributes only 17%, whereas in the Yangtze river basin in China, sewage accounts for only 18% of phosphorus pollution and agriculture for 80%.

Figure 15 shows the relation between phosphorus concentrations in runoff, global population distribution, and poverty. Similar to the maps of nitrogen

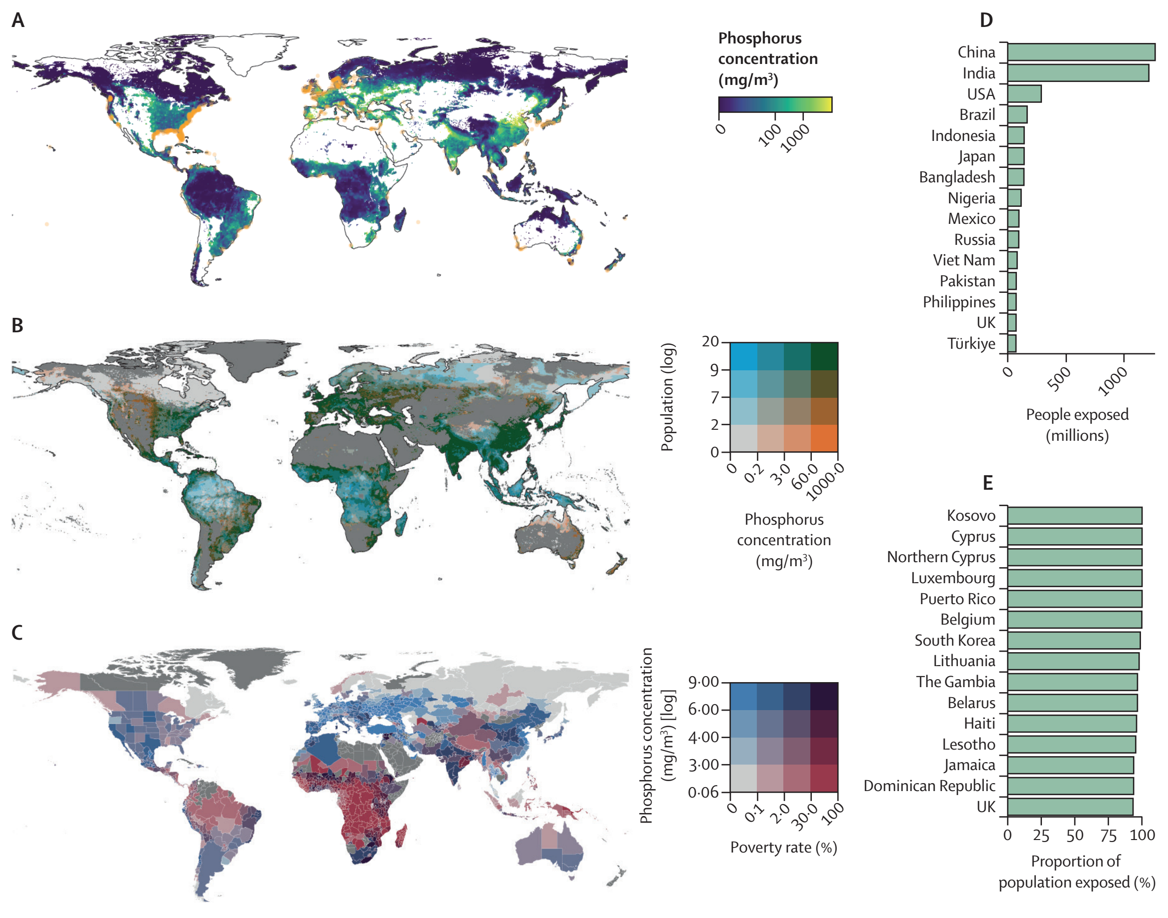

*Figure 15:* **Global distribution of phosphorus pollution impacts**

(A) Anthropogenic phosphorus concentration (2002–10) from agriculture and domestic sources in surface water. Concentrations in runoff act as a proxy for where the impacts of phosphorus pollution are most felt. Areas of coastal eutrophic and hypoxic areas are represented by orange dots.[184] (B) Phosphorus concentrations (2002–10) plotted against subnational population data (2020). Each colour break represents the intersection of both distributions using quartiles. (C) Phosphorus concentrations (2002–10) plotted against the proportion of people (on a subnational level) living in poverty (ie, below the US$1·90 poverty line as of 2018 [data source: World Bank 2021]),[131] with poverty as a proxy of vulnerability. Each colour break represents the intersection of both distributions using quartiles. (D) The ten countries with the highest absolute population exposed to high phosphorus concentrations. (E) The ten territories with the highest relative population exposed to high phosphorus concentrations. Note that Cyprus and Northern Cyprus are graphed as distinct territories.

distribution (figure 13), this map does not account for how phosphorus pollution can cause harm when transported downstream into shared lakes and oceans and does not take into account access to phosphorus fertilisers. Unsafe phosphorus concentrations coincide with high populations in China, Europe, eastern USA, and south Asia, and areas of increased poverty in south Asia, parts of China, southern Africa, and hotspots in central and west Asia. Some poor regions (eg, much of sub-Saharan Africa, northern Latin America, southeast Asia) are well within safe limits partly because of low fertiliser access and availability.

Tropical soils are often phosphorus depleted as a result of intense weathering and so require more fertiliser before phosphorus becomes available for crop growth.[191,192] As a result, when food is then exported from nutrient-depleted parts of LMICs, artificial nutrients are effectively imported by nutrient-rich countries and water pollution is offshored in return.[203,204] Another justice consideration is the limited availability of phosphorus deposits. Rock phosphate is a finite resource, and the availability of high-quality reserves could peak this century.[198,205] Minimising use of phosphorus and improving use efficiency and recycling would help to maintain reserves for future generations. Further justice considerations include lack of access to affordable phosphorus fertilisers affecting access to food, and geopolitical issues arising from unevenly distributed rock phosphate resources.[198,205]

## Blue water

Humans substantially influence the global hydrological cycle in the Anthropocene by altering surface water flows and draining groundwater reserves.[206] Most of these alterations are made to enable food production, with 70% of surface water withdrawals worldwide used for irrigation.[207] Water-supply dams, hydroelectric

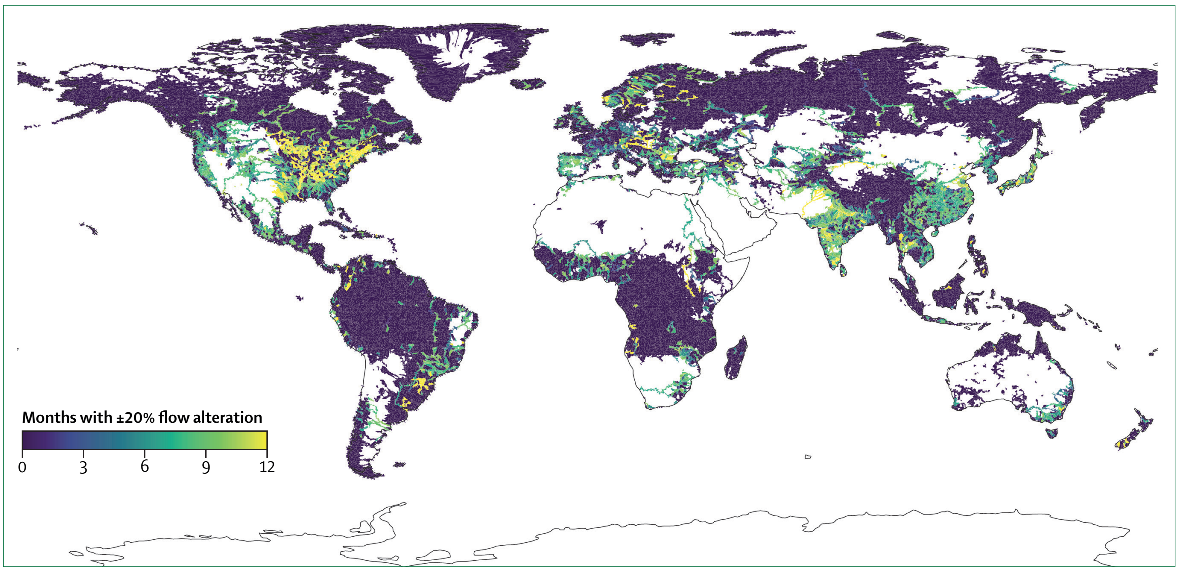

*Figure 16:* **Months per year in which modelled observed monthly surface water flows differ by >20% from modelled pre-industrial flows**
Such flow alterations (ie, outside the Earth-system boundary), which result from meeting the needs and aspirations of people, lead to a breakdown in function of the aquatic ecosystem, causing reduced fisheries production and the loss of other ecosystem services, which affects human health and livelihoods.

development, and groundwater extraction substantially disrupt natural patterns of ground and surface freshwater flows (ie, blue water), thereby displacing people[208,209] and threatening biodiversity[210] and ecosystem services (eg, inland and coastal fisheries that support the protein needs of billions of people).[211,212] Equally, land subsidence from excessive groundwater extraction causes infrastructural damage, and increases vulnerability to flooding, particularly in coastal regions that are already affected by rising sea levels.[213,214] Collectively, anthropogenic changes to the hydrological cycle are a barrier to the achievement of the SDGs,[215] which aim to meet the needs of the 30% of the world's population who do not have access to drinking water and the 60% who do not have sufficient access to sanitation.[216] Increasing water scarcity and declines in water quality are associated with 1·7 million deaths annually,[120] and increased rates of diarrhoeal diseases, which are the leading cause of infant mortality,[2] are responsible for approximately 7·7% of disability-adjusted life-years in children younger than 9 years.[217] Given that surface and groundwater flows cross national boundaries, the transformations necessary to meet the water-related SDGs and reverse these trends requires ESBs be translated to scales that are relevant for actors involved in the alteration of blue-water flows.

### *Safe ESBs*

Alterations of blue-water flows are leading to unsafe and harmful outcomes for the Earth and its people. The safe ESBs for blue water[10] integrate surface and groundwater flows in response to critiques of early planetary boundaries for freshwater, which included only the extent of surface-water consumption from river systems.[218] A separate planetary boundary for green water—the water in soil that is available to vegetation—was published in 2022; it incorporates the risks associated with large-scale alterations to soil-moisture conditions and complements the safe ESBs for blue water.[219] The safe ESBs for surface water and groundwater aim to protect functioning and biodiversity of aquatic ecosystems, and to reduce the risk of crossing tipping points associated with environmental degradation.

Generally, local-scale research is necessary to establish functional relationships between blue-water flows and important response variables (eg, biodiversity losses), which can then be used to define safe levels of change to blue water.[220,221] However, in the absence of such information, presumptive standards for safe levels of alteration form a necessary basis for global-scale boundaries. For the safe ESB for surface-water flows, we set as an area-based boundary (following Gleeson and colleagues[218]) of no more than 20% alteration of monthly surface water flows for all rivers globally, with 80% of flows left unaltered for environmental needs.[10,222–224] Several studies have shown that freshwater ecosystems can be sustained with low levels of flow alteration (ie, <20%) but that reductions in biodiversity become apparent when alterations exceed this level.[225,226] With modelled unaltered total global river discharge of approximately 38 150 km³ per year, the 20% alteration limit across all rivers corresponds to a maximum of 7630 km³ of alteration per year, assuming all flow alterations are due to withdrawal.

For groundwater, we also set an area-based safe ESB: annual groundwater drawdown, from both natural and anthropogenic sources, should be no more than the average annual recharge for all groundwater reserves. Although this ESB is inherently on a local

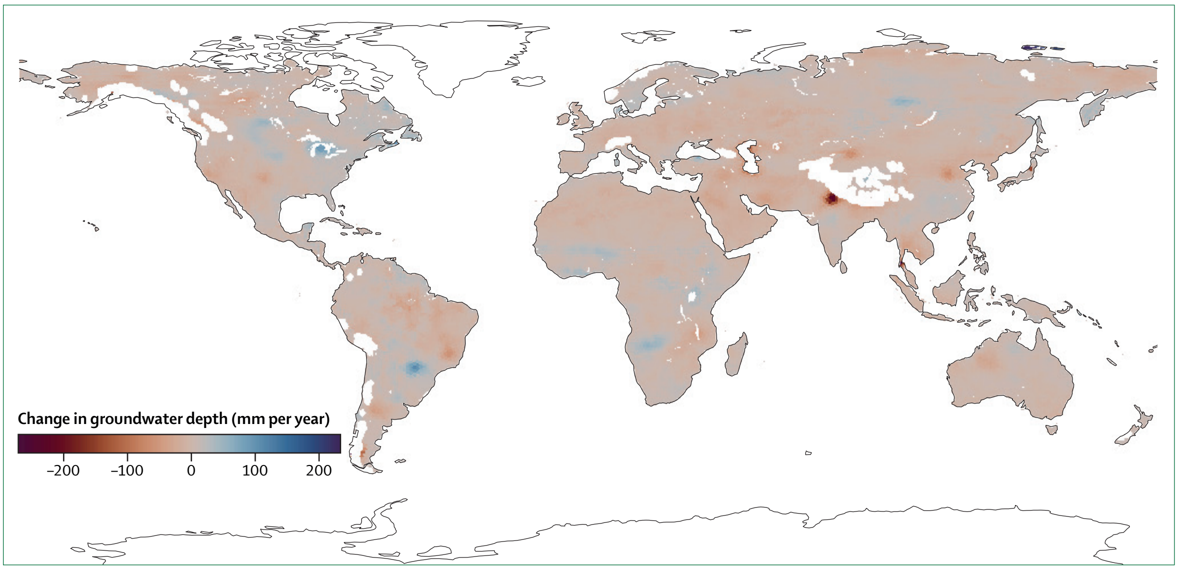

*Figure 17:* **Global change in groundwater depth**
The maps shows where the local-scale safe boundary is exceeded (as of 2016). Negative values on the scale correspond to regions where the average annual drawdown (from natural and anthropogenic factors) exceeds average annual recharge, which is outside the Earth-system boundary. Excess groundwater withdrawals help to meet short-term, localised social and economic needs. However, regions with declining aquifer volumes experience harm as a result of loss of groundwater-dependent ecosystem services.

scale (because drawdown refers to local groundwater levels), it aggregates to approximately 16 000 km³ per year globally according to the satellite record (2002–16).[10] When average annual drawdown of groundwater exceeds the average recharge, declines in aquifer volume occur, leading to reductions in surface-water flows[221] and an increased risk of land subsidence.[227] Because the safe ESB is based on current drawdowns versus recharge, it does not address environmental issues associated with already depleted aquifers (which could be restored through managed aquifer recharge). However, adherence to the ESB would help to ensure that surface-water flows would not be further reduced by over-extraction and that existing groundwater-dependent ecosystems would be protected. For both blue-water ESBs, the application of the boundaries at river basin and aquifer scales is likely to have greater meaning for planetary health and justice than the global aggregates.

To examine the spatial distribution of risks to the Earth system and planetary health, we analysed the output from a global-scale hydrological model and remotely sensed data on groundwater levels. These analyses identified regions where blue-water flows are substantially altered in an unsafe manner, especially in densely populated regions, with large areas of some river basins, such as the Ganges–Brahmaputra basins, showing unsafe changes in flow alteration for up to 12 months of the year (figure 16). These flow alterations are exacerbating threats to freshwater biodiversity and potential harms caused by declines in water security.[228,229] Many regions also exceed the safe boundary for groundwater, including parts of Brazil, southeast Asia, and the Upper Indus and Ganges–Brahmaputra basins (figure 17). Several of these regions (eg, central Thailand[230]) also experience substantial land subsidence associated with unsustainable groundwater use and related declines in surface flows.[231]

### *Just ESBs*

The justice implications for the safe ESBs for blue water are complex, with different contributions and challenges with respect to interspecies, intergenerational, and intragenerational justice. By setting aside an ecologically based volume of unaltered flows for the environment, and limiting annual groundwater drawdowns to the average recharge, the ESBs contribute to achieving interspecies justice and are consistent with many calls for the rights of the river.[232] However, the safe boundary for blue-water alterations raises concerns with respect to intergenerational and intragenerational justice, with particular challenges for transformation of our models of production and water management.[206]

Figure 18 illustrates where the safe ESBs are already being exceeded and how present generations are affected by past excessive groundwater drawdowns and surface-water alterations. Future generations will experience these and further unsafe conditions, thus compromising intergenerational equity. By setting the safe ESB for groundwater to recharge values, we do not correct for past excessive withdrawals and aquifer depletion.[233] In relation to intragenerational justice, figure 18 also shows transboundary river basins (ie, rivers that cross the boundaries of two or more countries) where

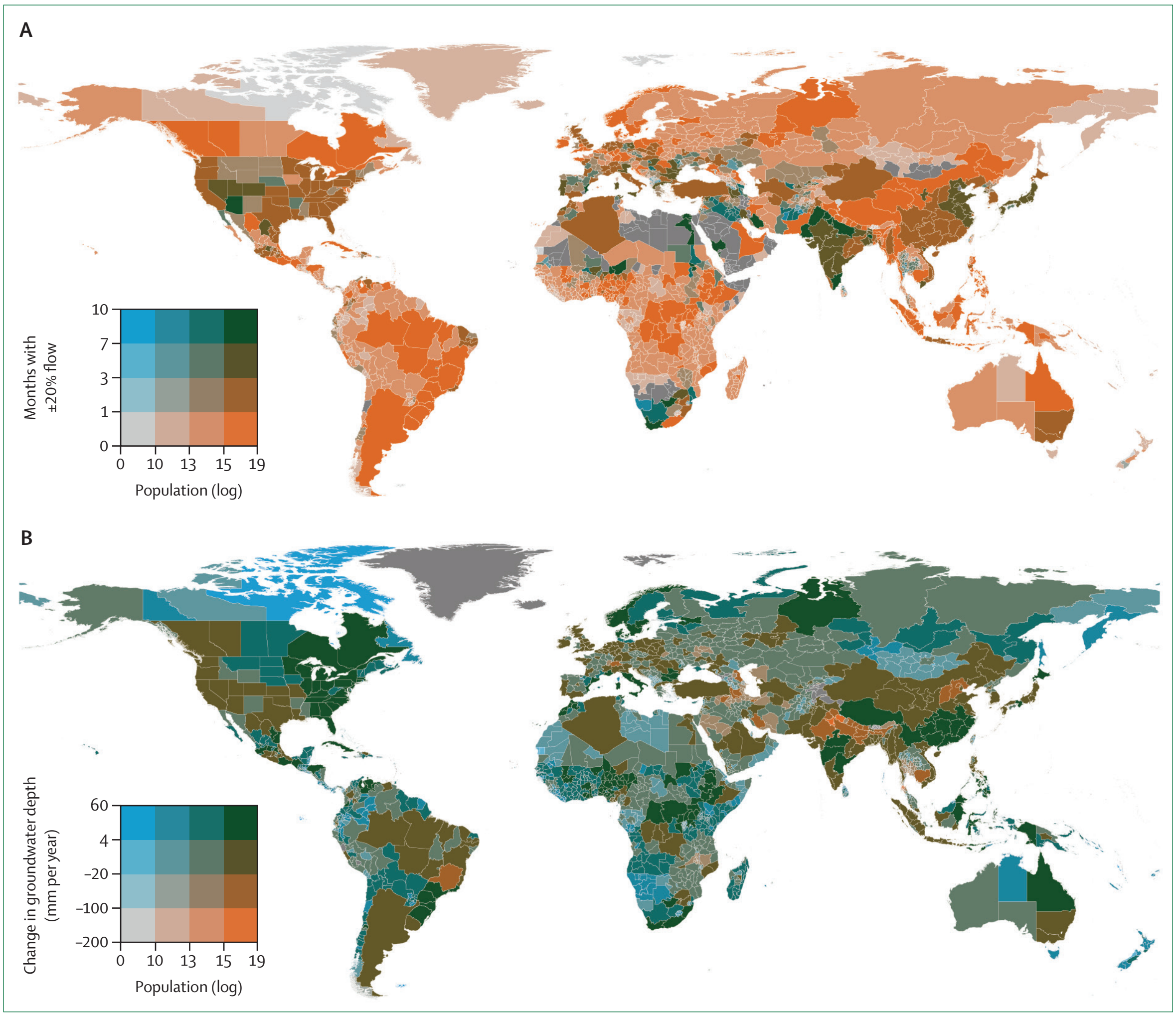

*Figure 18:* **Months per year with >20% alterations in surface water flows (A) and annualised changes in groundwater depths (B) plotted against populations**
Population is graphed on the sub-national level. In (B), negative values on the scale correspond to regions where the average annual groundwater drawdown exceeds average annual recharge. In both maps, each colour break represents the intersection of both distributions using quartiles.

downstream countries experience altered surface flows partly as a result of actions of upstream countries, such as on the Mekong Delta in Viet Nam or the lower Rhine in Germany and the Netherlands, raising international justice concerns.[234] Another potential concern is that the safe ESBs do not account for water quality, which is critical for human health. Therefore, to ensure just outcomes in terms of human health, the safe ESBs need to be complemented with water-quality standards, such as those of WHO.[235,236]

Billions of people worldwide are exposed to conditions resulting from the breaching of the safe ESBs for both surface water and groundwater (figure 18). Water flow is highly altered in many regions in high-income countries, with possible consequences for water supplies and ecosystems in other regions and neighbouring countries.[237] Water flow is also highly altered in many LMICs, including regions of Asia, many arid and semi-arid regions of Africa, and highly populated regions of South America (figure 18). In addition to the potential impacts on flow-dependent ecosystem services on which people rely, people in these regions are also at risk of exposure to declining water quality and the associated health outcomes. However, stringent adherence to safe ESBs for blue water could have implications for the billions of people living under conditions of water scarcity,[238] including for their livelihoods and food security. Water management and transformations in modes of production for farmers are crucial to avoid any potential trade-offs.

Figure 19 shows the relations between areas not meeting the safe ESBs for blue water with global distribution of population and poverty. Parts of west and east Africa, the Indo-Gangetic Plain, the Middle East, and central Asia exceed the safe ESBs as of 2020 but are likely to have fewer resources to manage these issues (figure 19). Figure 19 also shows relative differences within countries, such as the relatively higher rate of poverty in the arid western USA

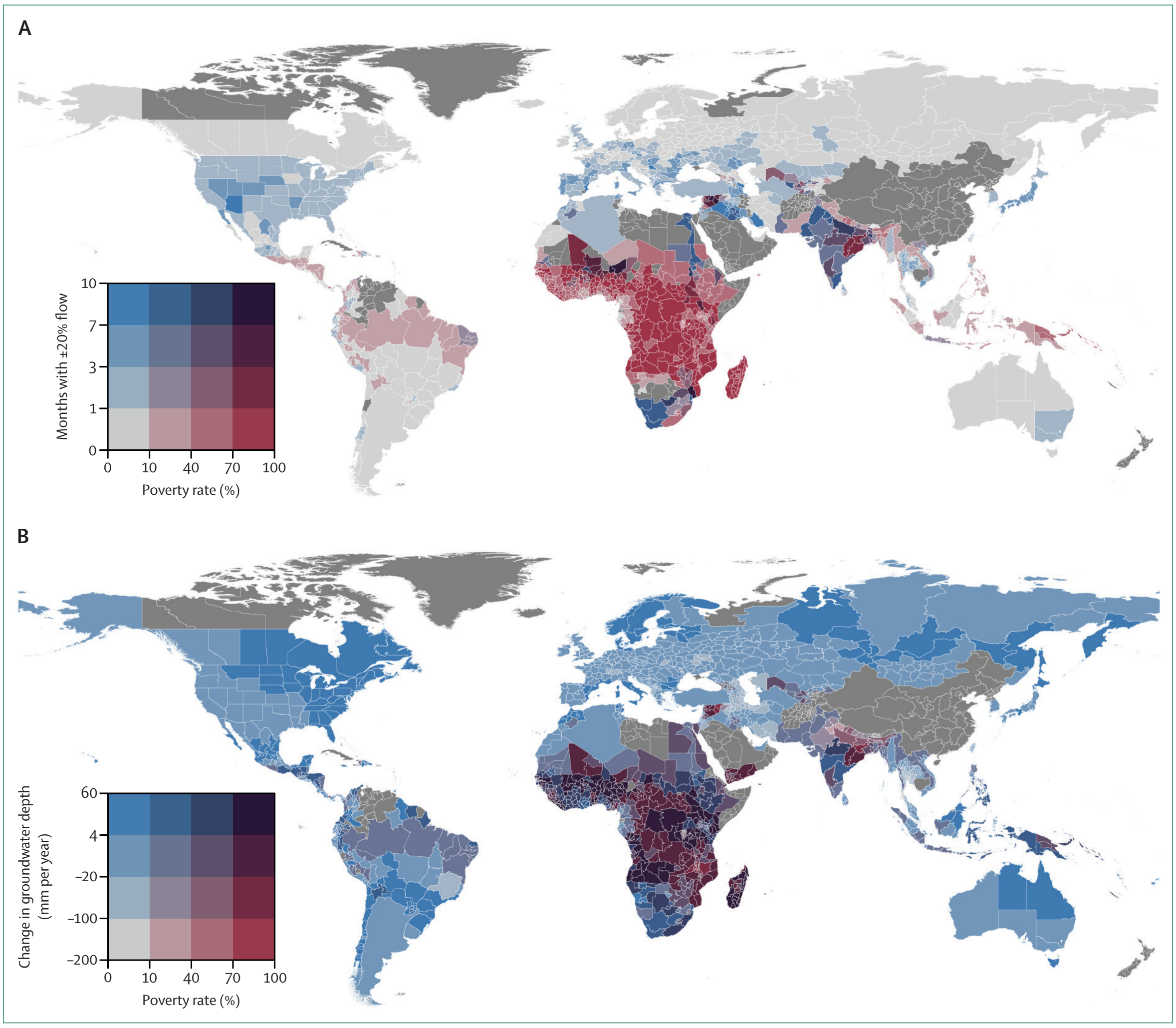

***Figure 19:* Months per year with >20% alterations in surface water flows (A) and annualised changes in groundwater depths (B) plotted against the proportion of people living in poverty**

Poverty, a proxy of vulnerability, was mapped as the proportion of people living below the US$1·90 poverty line at a subnational scale as of 2018 (data source: World Bank 2021).[131] Hotspots where water risk can imperil intragenerational justice include northern India, Iran, Afghanistan, Pakistan, sub-Saharan Africa, and southeast Africa (eg, Mozambique, Zimbabwe). Each colour break represents the intersection of both distributions using the Jenks algorithm.

compared with the rest of the country, highlighting that these problems cannot all be solved at the national level. Spatial mapping of water quality was not a part of our analysis, and therefore risks to vulnerable populations from declines in water quality and conditions when the safe ESBs have been breached might be underestimated.

Although adhering to the safe ESBs will contribute to intergenerational justice, there are substantial trade-offs between the restrictions on surface water alteration and groundwater extraction and the ability to access the necessary water for household, agricultural, and broader economic development. Existing transboundary and inter-community water-sharing agreements and the shifts from water as a common or publicly provided resource to a private good are additional challenges to meeting the safe ESBs. In private or full-cost pricing systems, restriction of water use often pushes up the price beyond affordability for poor people, with consequences for health and livelihoods. For example, Indigenous peoples worldwide are increasingly being disenfranchised from their water resources,[239] and hoarding as well as direct and indirect purchase of water in LMICs by wealthy national and international populations is becoming more common.[240] As a result, calls for water justice increasingly focus on competition between different groups of people.[241] Many states worldwide are moving water into the public domain to enable better regulation of it. However, simultaneously they are issuing permits and signing contracts in which entitlements to water have the characteristics of a property and are thus creating quasi property rights through the law.[242,243] Such actions hamper the redistribution of water without compensation of the quasi rights holders for expropriation. At the transboundary level, hundreds of water-sharing agreements leave little water for nature and are contested because the available water is viewed as inadequate to meet the needs and aspirations of countries.[244] Adhering to the safe ESB for surface-water alteration in transboundary river basins could ensure downstream communities have access to greater quantities of water, but achieving this in the context of existing international agreements will not be easy.

These potential trade-offs can be addressed by redesigning transboundary water agreements, rewriting permits and contracts to enable the state to recover the water in times of emergency or in the public interest, and engaging in massive demand-side water management, including substantial reuse of water, returning clean water to surface-water flows, and managed recharging of aquifers. A just allocation of water resources within the safe ESB needs to consider past institutions that have allocated water, re-examine development aspirations, redistribute such water equitably, and ensure multi-level distribution so all communities have sufficient access to water without contributing to crises for downstream communities.

## Aerosols and air pollution

Aerosols affect the Earth system, the climate, and human health. They can also affect soil, air, and water quality,[245] and can cause acid rain, plant mortality, and glacier and ice melting.[3] Aerosols can alter local and regional climates and can cause cooling or warming, depending upon their size, type, and location.[3] Aerosols can also help or inhibit cloud formation and contribute to extreme weather (eg, thunderstorms).[246] Aerosols can be natural (eg, dust, sea salt) or anthropogenic (eg, sulphates from coal, black carbon from diesel) and are spatially and temporally heterogeneous.[247,248] Concentrations of aerosols vary depending on factors including anthropogenic emissions, weather, and climate change.[249–251] Aerosols are sub-micron size particles and they constitute one of the many components of air pollution. Gases such as ozone, carbon monoxide, oxides of sulfur, and oxides of nitrogen are the other components of air pollution. Here, we assess the safe and just ESB only for aerosols, though we recognise the need for other pollution-related ESBs (panel 4).

Aerosol loading (ie, aerosol mass per unit volume of air) affects air quality, with justice implications. Air pollution is the fourth largest cause of ill health globally (after high blood pressure, dietary risks, and smoking).[252] $PM_{2·5}$ is the most relevant aerosol metric in terms of human health. Aerosols contribute to ambient air pollution, which accounts for 4·2 million deaths and indoor air pollution for 3·8 million deaths annually.[253] Long-term human exposure to air pollution, including $PM_{2·5}$, increases the risk of cardiovascular and respiratory diseases.[254]

### *Safe ESB*

Aerosols affect regional climate systems and potentially alter local conditions. For example, anthropogenic aerosols could have contributed to declines in Indian summer monsoon rainfall since the 1950s.[158,255] Sulphate aerosols injected into the stratosphere in the northern hemisphere could cause large deficits in Indian monsoon rainfall.[256–258] Natural aerosols injected into the stratosphere by major volcanic eruptions in the northern hemisphere have caused droughts in the Sahel, and eruptions in the southern hemisphere have been linked to greening of the Sahel region in Africa.[259] An additional interhemispheric difference in aerosol optical depth (AOD), a measure of the extinction of light by atmospheric aerosols, of 0·05 to 0·20 between the northern and southern hemispheres could lead to tipping of tropical monsoon patterns (ie, a shift towards a wet or dry Sahel) and is thus identified as a serious risk.[10] On the basis of the literature about the influence of aerosol loading on tropical monsoon systems, we set an interhemispheric AOD difference of less than 0·15 as the globally aggregated safe boundary for aerosols. Although understanding of the interaction between aerosols, clouds, and precipitation is improving, it is not well represented in climate models, which impedes better refined quantifications of the effects of aerosol on climate.

Aerosols have a short lifetime, which means that they concentrate close to their sources. Therefore, regional and local thresholds are a high priority (figure 20). On the basis of the literature on the influence of aerosol loading on regional hydrological cycles, we set an AOD of 0·25 as the safe regional and local boundary for aerosols.[9,10]

### *Just ESB*

Our analysis indicates that the globally aggregated safe ESB for air pollution based on interhemispheric AOD difference meets the criteria for interspecies, intergenerational, and intragenerational justice because it ensures the stability of tropical monsoons. Hence, we accept this ESB as safe and just. However, because interhemispheric AOD is an aggregate indicator for the emissions of aerosols and air pollution that cause substantial local-level harm, we complement the local and global safe ESBs with local air pollution standards for $PM_{2·5}$, which is closely related to AOD.[260] The WHO guidelines[261] suggest an annual air-quality limit of 5 μg/m³ $PM_{2·5}$ for all regions, with several interim targets of 35, 25, 15, and 10 μg/m³. We propose an additional just sub-global ESB of 15 μg/m³ $PM_{2·5}$ annually.[10] AOD and $PM_{2·5}$ concentrations are closely linked and have a roughly linear relationship;[260,262] adherence to an annual $PM_{2·5}$ limit of 15 μg/m³ would result in local AODs lower than the sub-global safe ESB of 0·25. In Europe, where the annual mean AOD is 0·15, this relationship suggests that $PM_{2·5}$ concentrations are around 14 μg/m³, which is close to estimates from ground-based

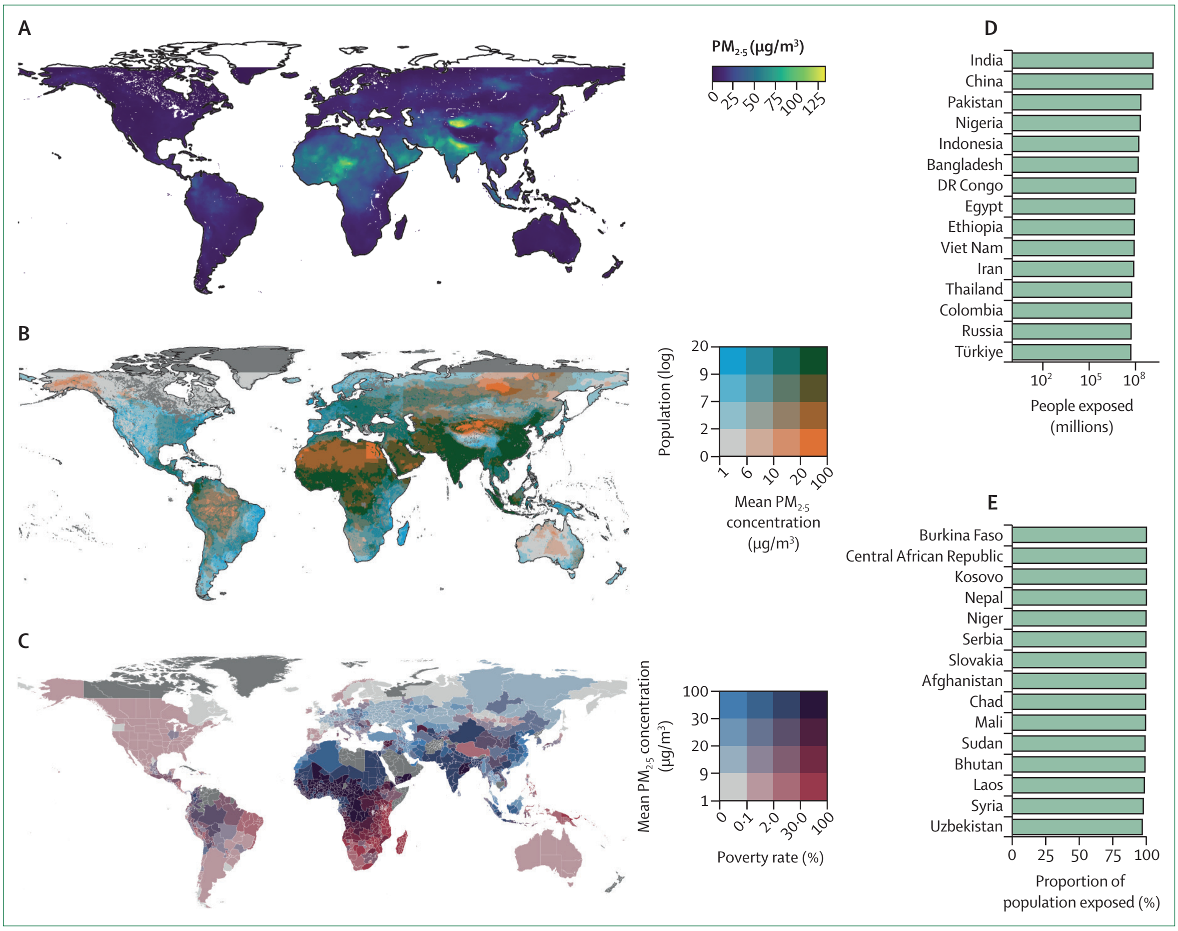

***Figure 20:*** **Global distribution of harm from air pollution.**
(A) Concentration of atmospheric PM$_{2·5}$ globally (at 0·01° resolution, based on data from the US National Aeronautics and Space Administration). (B) Concentration of atmospheric PM$_{2·5}$ plotted against population at 0·25° resolution. Each colour break represents the intersection of both distributions using quartiles.
(C) Concentration of atmospheric PM$_{2·5}$ plotted against the proportion of the population living in poverty (ie, below the US$1·90 poverty line as of 2018 [data source: World Bank 2021]),[131] with poverty as a proxy of vulnerability. Each colour break represents the intersection of both distributions using quartiles. (D) The 15 countries with the highest absolute number of people exposed to PM$_{2·5}$ above the suggested Earth-system boundary (<15 ug/m$^3$). (E) The 15 countries with the highest relative proportion of population exposed to PM$_{2·5}$ above the suggested Earth-system boundary (<15 ug/m$^3$).

monitors.[263] For South Asia (AOD 0·35) and east China (AOD 0·4), the estimated annual mean PM$_{2·5}$ concentrations are 23·5 µg/m³ and 25·8 µg/m³, respectively—ie, the regional safe and just ESBs have already been crossed.

Figure 20 shows part of the distributional challenge of the injustices of harm from air pollution in absolute terms per region. This map combines areas with high air pollution load (as a measure of air-pollution exposure) and poverty (as a measure of air-pollution susceptibility). Air pollution is most severe in south Asia, whereas poverty is highest in Africa (figure 20). Poverty limits people's ability to adapt in the face of air pollution—eg, to use air filters to reduce indoor air pollution or less polluting stoves and heating sources—and their access to health care. In several countries, the entire population live in areas where the ESB has been transgressed, with large numbers of people affected. However, figure 20 does not account for indoor air pollution[264] resulting from the use of unsafe fuels and technologies for cooking, heating, and lighting. Although ambient air pollution affects all countries to varying extents, indoor air pollution is highest in LMICs, especially in the Western Pacific and southeast Asia regions. In sub-Saharan Africa, only 15–17% of households use clean fuels and technologies for cooking.[265] Indoor air pollution is the leading risk factor for premature deaths in low-income countries, and disproportionately affects women and children.[266] Mapping where air-quality standards are exceeded and how this overlaps with the distribution of poverty allows for partial identification of the people most vulnerable to air pollution, and thus most at risk of harm.

WHO estimates that around 99% of the global population lives in areas where the annual mean ambient

$PM_{2·5}$ concentrations are higher than 5 µg/m$^3$.[267] About 85% of people live in areas with annual $PM_{2·5}$ concentrations above the harm threshold that we defined, 15µg/m$^3$.[268] Concentrations are highest in cities in Asia and Africa.[267] High concentrations in North Africa and Middle Eastern countries are due to natural dust sources, whereas in cities in south and east Asia low air quality results primarily from anthropogenic aerosol sources.[181,269,270] Urban populations in growing megacities, especially in south Asia and Africa, are heavily exposed to anthropogenically produced $PM_{2·5}$, and annual increases in the population exposure to air pollution ranges from 1% to 18% between 2005 and 2018.[271,272] The impact of this exposure is skewed towards LMICs, where more than 90% of all deaths from air pollution occur.[273] Premature mortality due to air pollution is influenced by age distributions and other health and demographic factors,[274] and thus swift action is needed on air pollution in low-income and middle-income countries. Potentially controllable anthropogenic emissions contribute to a reduction of around 1·7 years of global average life expectancy, 1·1 years of which can be attributed to fossil fuel use.[275] Other justice issues relate to the large inequalities between who produces air pollution and who experiences the ill effects.[10,82]

## Earth-system implications of meeting minimum access needs

### *Identification of minimum access and associated material implications*

In this section, we estimate the biophysical pressures on the Earth system associated with minimum access to basic goods and services, which first requires establishing what minimum levels entail. Table 1 presents the results of our literature review to quantify the two conceptual definitions of just minimum access to basic goods and services—ie, basic dignity (level 1) and escape from poverty (level 2). We operationalise the concepts of dignity and escape from poverty from a material rather than a monetary perspective. Our technical approach is based on the methods of Rammelt and colleagues[13] (summarised in the appendix [pp 2–8]). In this study we apply their methods[13] to calculate the environmental impact associated with provision of only minimum access to food, water, energy, and infrastructure for the safe and just corridor. We have not included access to all necessary minimum goods and services, such as education and health care. We acknowledge the limitations of this pragmatic analysis and anticipate that future research will be able to integrate more components of minimum access. However, we have addressed the limitations of our approach to some extent by including a sensitivity analysis and adding further energy requirements in line with a decent living energy framework, as we will discuss in more detail later.

| | Minimum access (per person) | Resulting biophysical pressure (2018) | Resulting biophysical pressure (2050) |
|---|---|---|---|
| **Energy (electricity)** | | | |
| Level 1 | 74 kWh per year | 581·0 TWh per year | 725·2 TWh per year |
| Level 2 | 255 kWh per year | 1989·8 TWh per year | 2483·4 TWh per year |
| **Water** | | | |
| Level 1 | 50 L per day | 142·3 km$^3$ per year | 177·7 km$^3$ per year |
| Level 2 | 100 L per day | 284·7 km$^3$ per year | 355·3 km$^3$ per year |
| **Food** | | | |
| Level 1 | 2100 kcal per day | 25·0 million TJ per year | 31·2 million TJ per year |
| Level 2 | 2500 kcal per day | 29·8 million TJ per year | 37·2 million TJ per year |
| **Infrastructure (housing)** | | | |
| Level 1 | 7 m$^2$ | 5·5 million Ha | 6·8 million Ha |
| Level 2 | 15 m$^2$ | 11·7 million Ha | 14·6 million Ha |
| **Infrastructure (transport)** | | | |
| Level 1 | 3500 passenger-km | 27 300 billion passenger-km per year | 34 072·6 billion passenger-km per year |
| Level 2 | 4500 passenger-km | 35 100 billion passenger-km per year | 43 807·6 billion passenger-km per year |

Level 1 describes the minimum access to resources needed to live a life of basic dignity, while level 2 describes the minimum access needed to enable escape from poverty. The biophyscial pressures were calculated as if all people in the world were consuming at minimum access levels and no more. Note that this table does not show the entire spectrum of needs that we accounted for when estimating the impacts of meeting these needs. Our aim was to estimate the biophysical impacts, and the causes are therefore distributed across different access domains where they best serve that goal, which helped to avoid double counting. The appendix (pp 2–3) includes a comparison of related minimum access values from other sources in the literature, derived from Rammelt et al, 2023.[13]

***Table 1:* Per-person minimum access levels and resultant biophysical pressure in 2018 and 2050**

For water, our quantification of minimum access level 1 adopted WHO's definition of intermediate access (ie, 50 L per person per day for drinking, cooking, and hygiene), whereas for level 2 we adopted WHO's definition of optimal access (ie, 100 L per person per day, which meets optimal basic consumption and hygiene needs).[276] We excluded water use embedded in food and energy production, because such use is captured in the food and energy access impacts.[13]

For minimum access to food, level 2 was represented by the EAT–*Lancet* Commission diet[119] (ie, 2500 kcal per person per day). For level 1, we used the same dietary composition, but reduced the caloric intake to the minimum that WHO judge necessary in emergency situations (ie, 2100 kcal per day).[277] The WHO diet represents an intake required for survival and modest physical activity.[13]

For minimum access to energy, we focused only on direct electricity services at the household level, and used the following World Bank levels:[278] for level 1, we

| | 2018 | | 2050 | |
|---|---|---|---|---|
| | Minimum access (level 1) | Minimum access (level 2) | Minimum access (level 1) | Minimum access (level 2) |
| Relative further impact (%) | 0·01–14·78 | 0·12–26·47 | 0·01–14·78 | 0·12–26·47 |
| Billions of people below minimum access level | 0·16–3·02 | 0·38–3·36 | 0·19–3·77 | 0·48–4·19 |
| Share of population below minimum access level (%) | 1·99–38·74 | 4·9–43·09 | 1·99–38·74 | 4·9–43·09 |

Further relative impacts refer to the additional impacts on the Earth system from achieving minimum access levels, meaning that everyone living below the minimum access levels achieves exactly those levels of access, while other consumption levels remain the same. The range shows the lowest and the highest impacts across the domains collectively in the analysis (with associated number and share of total population below access). Typically, the highest impacts are on the climate domain. The relative impacts of the individual domains are presented in the appendix (p 7). Level 1 describes the minimum access to resources needed to live a life of basic dignity, while level 2 describes the minimum access needed to enable escape from poverty.

*Table 2:* **Further relative impacts of providing minimum access to resources to people without access**

used access to 0·2 kWh per person per day, which implies electricity availability for at least 8 h per day (3 h per evening) for the use of medium-power appliances (eg, refrigerators, water pumps). For level 2 access, we used 0·7 kWh per person per day, which suggests electricity availability for a minimum of 16 h per day (4 h per evening) including some use of high-power appliances (eg, washing machines), with a maximum of 14 disruptions per week. Future analyses should also include non-electrical energy, firewood, or gas for cooking and heating; energy requirements for additional productive uses, such as health care and education; and energy consumed in the production of products and infrastructures (other than energy consumed for housing, which we have included).

Minimum access to infrastructure was represented by minimum access to housing and transportation. The minimum access levels for housing were derived from policy documents detailing minimum usable floor area per person (which ranged from 7–13 m² in Taiwan[279] to 14–15 m² in Europe[280]). In our analysis, we used 7 m² for level 1 and 15 m² for level 2, the latter of which includes space for sleeping, cooking, and bathing. For minimum access to transportation, little relevant academic literature or policy was available. We selected 3500 passenger-km per year for level 1 and 4500 passenger-km per year for level 2 to define decent access to mobility, which has been proposed as a reasonable range for the EU.[281]

We calculated the biophysical pressure (in terms of consumption of energy, food, water, etc) associated with hypothetically meeting all of these minimum access needs (both level 1 and level 2) for all people in 2018. This calculation entails increasing consumption of those who live below the level and decreasing consumption for those who live above the level. For example, humanity would consume 581·0 TWh of electricity per year if everyone lived at access level 1 (table 1). We also extrapolated these pressures to 2050 by assuming a population of 9·7 billion people based on UN projections (ie, the pressure per person multiplied by projected population size; table 1).[282] The addition of further minimum access components that were not included,[13] such as industrial production, education, and health care, would increase the biophysical pressure of providing minimum access and further reduce the safe and just corridor, and thus would not alter our general conclusions.

## Additional biophysical impact of providing just minimum access

We now turn to estimating the additional biophysical impacts on ESBs that would occur if the consumption of people who live below minimum access levels was hypothetically increased to those levels and consumption of those above the minimum access level remained constant. To estimate these additional impacts (on top of current impacts), we used the global income distribution as a proxy for the distribution of the effect on the biophysical domains.[13] We identified the access gap as the number or proportion of people living below minimum access levels 1 and 2 to generate the total amount of additional impacts in 2018 and in 2050 (table 2). In extrapolating to 2050, we assumed that, apart from population growth, all other conditions remain constant—such as inequality (apart from closing the minimum access gap), consumption levels, and economic and technological development. A sensitivity analysis is presented in the appendix (pp 8–10), showing that technological developments are unlikely to eliminate the urgent need for transformations to enable the global community to live within ESBs.

Table 3 shows relative further impacts on top of existing pressures on the biophysical domains (eg, the proportion of additional climate impacts associated with ensuring that everyone on Earth has access to a minimum amount of food, water, energy, etc) and the number and proportion of people without minimum access (or more precisely, the number and proportion of people who do not yet generate the impacts, such as emissions, that are associated with the achievement of minimum access). Table 3 presents this information as ranges across the different biophysical domains—for example, the number of people with level 1 minimum access in 2018 is between 0·16 billion (the number associated with sulphur dioxide) and 3·02 billion (the number associated with climate). As mentioned previously, we used income distribution as a proxy for the distribution of the different biophysical impacts (eg, emissions) associated with gaining minimum access. We can therefore report only the number of people contributing less than the different biophysical impacts (eg, emissions) that are associated with having achieved minimum access—ie, we cannot report on the number of people lacking minimum access to food, or to energy, separately. Meeting minimum access will have the largest impact on the ESB for climate. Hypothetically, achieving minimum access for the 38·74% (for level 1) and 43·09%

| | Climate (gigatonnes $CO_2$e per year) | Groundwater (km³ per year) | Surface water (km³ per year) | Land* (millions of Ha) | Phosphorus (Tg per year) | Nitrogen† (Tg per year) | Sulphur dioxide (millions of tonnes per year) | Nitrogen oxides (millions of tonnes per year) |
|---|---|---|---|---|---|---|---|---|
| **2018 (population 7·8 billion)** | | | | | | | | |
| Current impact | 38·00 | 1071·69 | 3215·08 | 5847·72 | 21·92 | 117·14 | 109·30 | 10·29 |
| Level 1 minimum access for everyone | 19·12 | 208·44 | 625·33 | 1333·62 | 3·91 | 24·13 | 1·44 | 0·99 |
| Level 2 minimum access for everyone | 26·91 | 288·74 | 866·21 | 1590·06 | 4·66 | 28·73 | 4·94 | 3·38 |
| **2050 (population 9·7 billion)** | | | | | | | | |
| Current impact | 47·43 | 1337·56 | 4012·68 | 7298·43 | 27·35 | 146·20 | 136·42 | 12·84 |
| Level 1 minimum access for everyone | 23·86 | 260·15 | 780·46 | 1664·47 | 4·89 | 30·12 | 1·80 | 1·23 |
| Level 2 minimum access for everyone | 33·58 | 360·37 | 1081·10 | 1984·53 | 5·82 | 35·85 | 6·17 | 4·22 |

Level 1 describes the minimum access to resources needed to live a life of basic dignity, while level 2 describes the minimum access needed to enable escape from poverty. The table shows the impacts if all people in the world were consuming at minimum access levels and no more. $CO_2$e=carbon dioxide equivalents. *Level 1 and level 2 for everyone accounts for the biosphere functional integrity safe boundary of a minimum of 20% of semi-natural habitat per km². To accommodate this requirement for vegetated areas in human-modified lands, the required land area is increased by 20%. †Impact from synthetic nitrogen fertilisers.

*Table 3:* **Biophysical impact if all humans consuming resources at minimum access levels in 2018 and 2050**

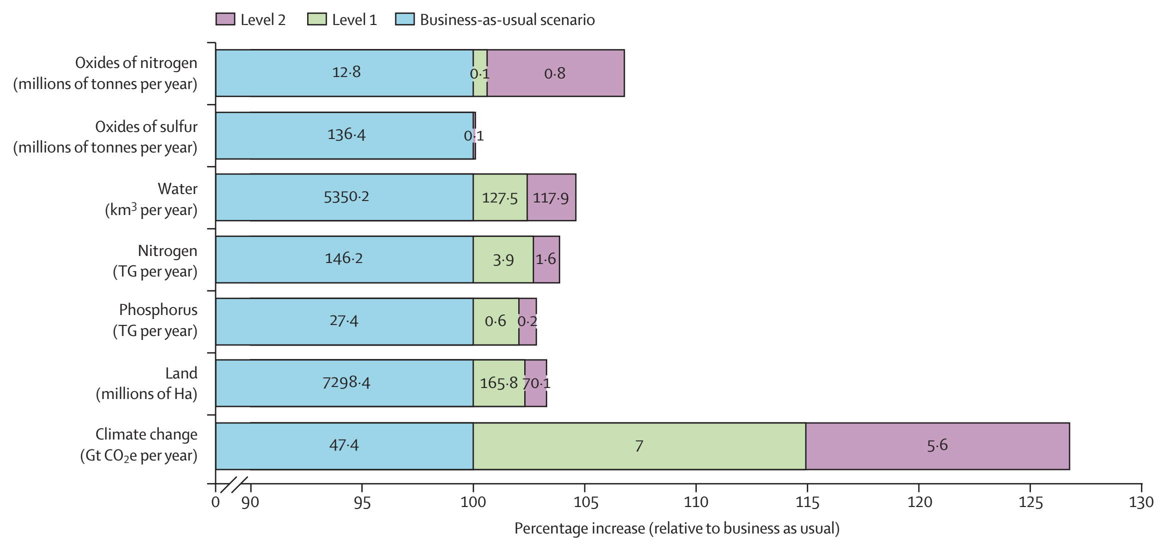

*Figure 21:* **Additional biophysical pressure of providing minimum access levels 1 and 2 by 2050 to those living without minimum access without transformation of the global economy**

Provision of minimum access to all is compared with the business-as-usual scenario (in which distribution of both resources and technologies remains the same as in 2018). Our sensitivity analyses to assess the impact of our assumptions resulted in only minor changes to these findings (appendix pp 8–10). $CO_2$e=carbon dioxide equivalents.

(for level 2) of the world's population who do not have this level of access would add between 14·78% (for level 1) and 26·47% (for level 2) further relative impact on top of the existing impact on the climate system.

We have already transgressed several ESBs,[10] even though hundreds of millions of people do not meet the minimum access levels for all domains.[13] Meeting the minimum access needs of those below the two levels in 2018 would have a substantial impact on the climate, and somewhat lesser effects on other biophysical domains (if other drivers remain the same). This extra pressure could be reduced through transformations—eg, by reducing the impact of the top 7–15% emitters of greenhouse gases and other pollutants.[13] In the absence of such transformations, extrapolation of our findings to 2050 suggests a substantially increased risk of further transgressing the safe and just ESBs if minimum access is achieved for all people, with particular effects on climate, followed by nitrous oxide concentrations, water, nitrogen pollution, the amount of land required, phosphorus pollution, and sulphur dioxide (figure 21). Thus, adhering to ESBs requires a combination of redistribution of resources and responsibilities, new forms of economic systems that address production, consumption, and investment patterns, and transformation of governance.[13,283,284]

We conducted a sensitivity analysis to assess the impact of our assumptions. Adjustment of the minimum access levels by 10% or use of the upper and lower values of the 95% CI of UN population estimates for 2050 (appendix pp 8–10) had little effect on our results. However, our results changed substantially—with increased impact on biophysical domains (appendix pp 8–10) when we used wealth distribution rather than income distribution to estimate additional impacts on the Earth system. Nonetheless, we have confidence in our use of income distribution given that wealth is not necessarily the best proxy for consumption patterns. We also explored the potential effects of adding further energy uses that were not accounted for to our analysis. The Decent Living Energy framework includes health, education, and communication, which account for roughly 20% of the total recommended energy.[285] The addition of 20% more energy to our minimum energy levels per person did not substantially increase biophysical pressure for climate (eg, doing so would raise the additional climate impacts from those currently without minimum access to resources gaining access from 14·78% to 14·86% for level 1, and from 26·47% to 26·81% for level 2; these changes are expressed in relative terms in the appendix, pp 9–10). It is important to note that climate impacts extend beyond the energy dimension of minimum access, to include impacts from heating and transportation (accounted for in the infrastructure category) and impacts from food production, which has a proportionally greater climate impact than household energy consumption. Because access to food produces a much larger impact than access to energy, a 20% increase in our definition of minimum access to energy would not lead to a 20% increase in total impact. The adjustment had even less effect on water and land systems. It had a notable effect on air pollution only—eg, the impact of nitrogen oxide would increase from 6·75% to 9·51% for access level 2.

Our 2050 estimates do not take into account any changes in technology, efficiency, or energy provisioning. As a thought experiment, the results provide a call for transformations. Much uncertainty remains as to what might happen with regard to supply-side and demand-side changes, not only with regard to carbon, but also with regard to energy, material, land, and water resources. That said, we tested 20% cumulative technological efficiency gains until 2050 in a sensitivity analysis. Such gains would lower climate impacts to 11% for level 1 minimum access and to 17% for level 2 access (compared with our earlier estimates of 15% and 26% without technological development (appendix pp 6–7 for the full results).[13] The International Energy Agency suggests that the average global emissions intensity of final energy (ie, carbon dioxide per unit of final energy delivered) will fall by around 30% by 2050.[286] When we used this estimate instead of the 20% efficiency gain in a sensitivity analyses, the climate impacts are further lowered to 9% for level 1 and 16% for level 2.

### *Safe and just corridor: safe and just ESBs and just minimum access for all*

Having defined the ESBs and explored the global-scale exposure and vulnerability to conditions when the ESBs are transgressed, we established the base of the safe and just corridor based on per-person just minimum access level (ie, level 2, escape from poverty) for all people (table 3). In estimating the base, we did not focus on if minimum access were met for everyone without it (as per in our calculations in the previous section), but rather on if everyone only had the level 2 minimum access needs met and no more. Conversion of the impact of achieving such minimum access to a common biophysical unit allowed for comparisons with the safe and just ESBs and provided a basis for the corridor. However, some unit conversions were necessary to harmonise the safe and just ESBs with the minimum access levels for climate, blue water, the biosphere, nitrogen, and phosphorus (appendix pp 9–10).

A potential corridor emerges between the safe and just ESB ceiling and the base—the lower biophysical boundary needed to justly meet minimum access level 2 (escape from poverty) for all people (figure 22). This corridor represents the excess of ecospace—that is, the environmental utilisation space available if the Earth's resources are to be sustained and reused[287]—when the just minimum access needs are deducted from the total ecospace. It delimits the space in which human development on Earth is feasible, but is not in itself just, because resources can still be unjustly allocated within this space.[288]

After harmonising the units for the safe and just ESBs and the minimum access levels, our analysis showed that humanity is outside the safe and just corridor for most domains (figure 22A). We could not calculate minimum access levels for biosphere functional integrity, and hence this is not included in the calculations of the ecospace. The two blue-water boundaries are inside the corridor, meaning that humanity would be within both boundaries if everyone lived at the minimum access level, but only because this quantification is in volumetric terms at a global scale, whereas the effects of blue-water alteration and thus of adhering to the ESBs play out at local and regional scale, as is evident when analysed in spatial terms (figures 16, 17). In other words, globally there is enough water, but because it is not generally possible to reallocate large volumes of water from water-rich to water-scarce regions, there are large areas of the world where people are being exposed to significant harm due to blue-water shortages and conditions in which the ESBs have been transgressed. Thus, it is important to consider regional as well as global patterns.

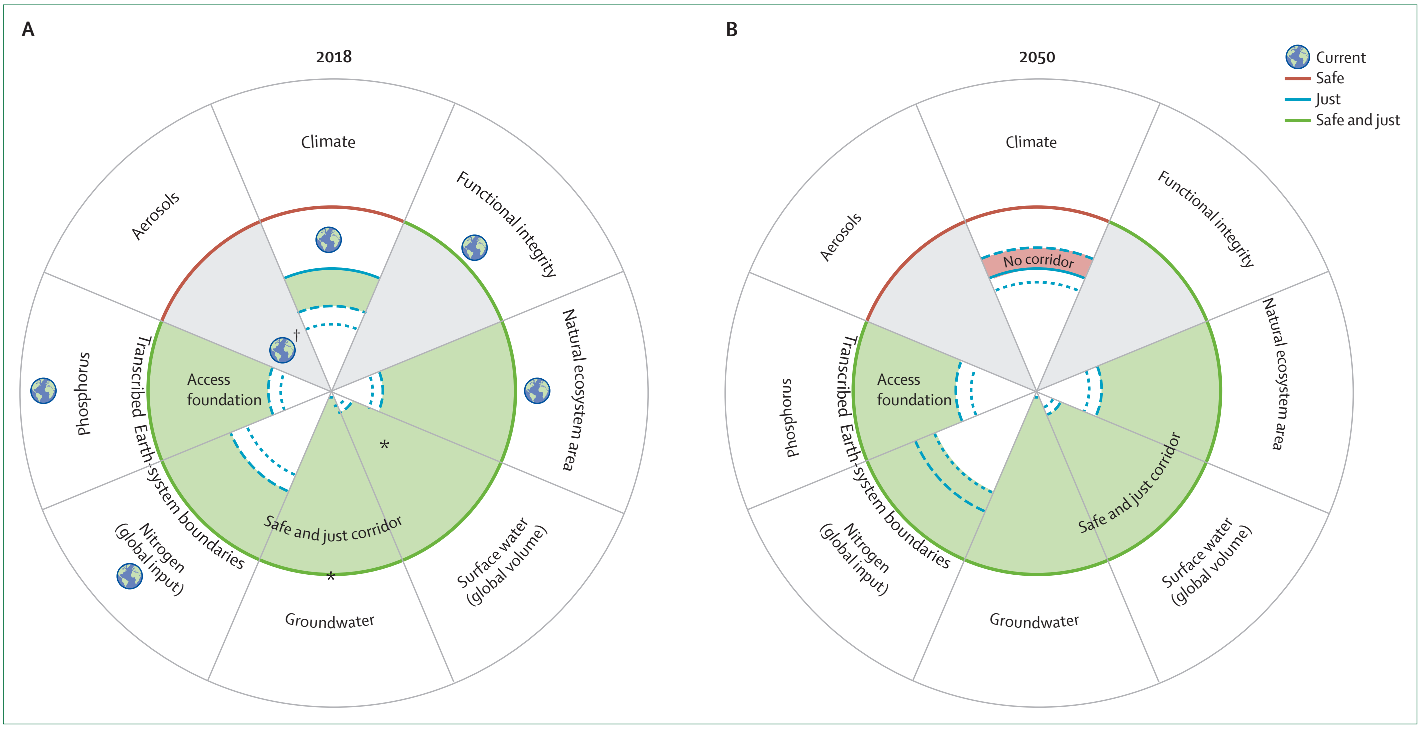

***Figure 22:* Quantification of the safe and just corridor in 2018 (A) and projections to 2050 (B)**
In (A), the base of the corridor is calculated based on supplying minimum access needs at level 2 for all people on Earth as of 2018 (7·8 billion people). There is a safe and just corridor (green) for climate, natural ecosystem area, surface water, groundwater, phosphorus, and nitrogen. For aerosols and functional integrity, we have not been able to calculate the base, and so we have not been able to define a safe and just corridor. Humanity is outside the safe and just corridor for climate, natural ecosystem area, phosphorus, and nitrogen. In (B), we assumed a population of roughly 9·7 billion people in 2050. This increase in population raises the Earth-system pressure involved to provide minimum access level 2 to all, thereby shrinking the corridor in all domains. For climate, the minimum access levels exceed the Earth-system boundaries, therefore leading to an absence of the corridor. In both (A) and (B), the base is visualised at minimum access level 2 (dashed line), with minimum access level 1 additionally plotted for reference (dotted line). The grey shows domains without access quantification (aerosols and biosphere functional integrity). *Earth-system boundaries are not crossed when aggregated to volumetric budgets globally, but are crossed at local or regional scales. †The safe aerosol Earth-system boundary is not crossed globally, but both the safe and the just boundaries are transgressed at local or regional scales.

In addition to the world's position as at 2018 relative to the safe and just corridor, our analysis shows that the corridor is expected to shrink in coming decades (figure 22B) because of the additional effects on the Earth system of meeting minimum access needs of a growing population (in the absence of efforts to redistribute and transform technologies and the societal system). The effects are particularly pronounced for the climate: providing only minimum access level 1 for the global population by 2050 pushes expected global warming beyond the safe and just ESB, thereby making it impossible to identify a safe and just corridor for climate (figure 22B) in a business-as-usual scenario. Radical decarbonisation efforts in combination with redistribution will be needed to open up a safe and just corridor for climate in the future. Across all other domains, a safe and just corridor is possible in 2050, although the corridor for nitrogen inputs shrinks more rapidly than that for the other domains nearing 2050 (figure 22A–B). If everything else remains constant, the growing population alone is likely to push humanity far outside this shrinking corridor in several domains. Thus, living within ESBs while meeting the just minimum access needs of poor and marginalised populations will require additional transformations. Ensuring that the remaining ecospace is allocated in a way that environmental and social goals are achieved will necessitate further transformations in technology and governance systems.[289] In Part 3, we reflect on how to translate ESBs to policies for cities and businesses.

## Part 3: Linking ESBs to key actors via cross-scale translation

### Cross-scale translation: why cities and businesses?

For humanity to reside within the safe and just corridor, the safe and just ESBs that we have defined need to be translated into actionable terms for stakeholders and actors—at the supranational, national, city, household, industry, and business levels. Stakeholders and actors at different levels can play important, complementary roles in operationalising ESBs. The UN can set shared societal goals and coordinate global policy responses and international agreements, which national governments can then implement.[289] Individual and household choices influence resource consumption, environmental impacts, and business practices within the limits of structural constraints.[290] Nations, cities, and businesses, through their dominant modes of production, consumption, and trade and their decision-making power, can profoundly affect critical Earth systems.[291] Cross-scale translation can help all stakeholders and actors to identify their fair shares of ESB-aligned resources and responsibilities, which can then be mainstreamed into decision making and practices, within and across territories or value chains. Guided by ESBs and informed by their fair shares of resources and responsibilities, actors can plan and set targets individually and collectively across geographical and temporal scales, with progress against those targets monitored and assessed at regular intervals.[292–294]

In this Commission, we focus on cities and business actors because both are responsible for large shares of environmental pressures across all ESBs.[295–304] They are thus key actors to mobilise to enable living within the safe and just corridor. Cities and businesses can reduce environmental impacts through enhanced efficiency in production and distribution processes, technological innovations, adoption of circular economy business models, and innovative management, policy, and planning schemes.[292,293,305–312] They are nimble and flexible actors that can rapidly initiate changes compared with governments. However, few existing studies focus on cities and businesses in a cross-scale translation context—most tend to focus on particular countries or industries.

Many cities and businesses are already proactive in terms of environmental sustainability.[309,313–319] Many cities are setting climate and sustainability targets through local initiatives and networks,[320–322] and others are guided by regional or global targets, such as the SDGs and the New Urban Agenda.[323,324] Cities are also taking leadership roles in adopting urgent climate action, including through committing to working towards net-zero targets by 2050 (adopted by more than 1300 cities).[294,325–327] Companies are supporting the SDGs[293] and integrating science-based targets into their risk-management strategies to ensure long-term business sustainability. In response to investor and consumer demands, companies are measuring, monitoring, and disclosing some aspects of their environmental footprints, including carbon emissions, water use, waste management and carbon offsets, social contribution indicators, and future targets. Disclosure, however, can be patchy, and is often limited to jurisdictions where it is required and to profitable companies with the resources to develop sustainability reports.[328–330] Additionally, greenwashing has been identified in the reporting of environmental, social, and governance data by large firms.[331] Establishing scientifically robust and transparent methods of translation for the ESBs could help to narrow the scope for greenwashing and facilitate science-based target setting and subsequent actions to move society into a safe and just corridor. Science-based targets are measurable, actionable, and time-bound,[332,333] and should be dynamic, fair, and adjustable to reflect new scientific evidence.[332] Targets should also be ambitious enough to enable actors to move faster towards and remain within ESBs.[294] So far, the uptake of science-based targets in corporate reporting and strategies has been largely limited to carbon emissions.[294]

### Existing translation efforts

Allocation procedures often start with downscaling to an individual unit and then upscaling the individual share to a higher level—eg, the nation level, an industrial sector, or the product level.[334] Both the downscaling and upscaling processes are underpinned by particular sharing approaches. Studies on translation of similar frameworks, including the planetary boundaries,[7,9] have adopted as many as 30 allocation approaches, informed by various justice principles.[335–337] We discuss examples of sharing approaches relevant for cities and businesses (appendix pp 18–19). Country and city translation is commonly undertaken based on the equality-sharing approach enacted as equal per-person allocation, enabled by the availability of globally harmonised population data. Translation to sectors and companies commonly applies the legacy-sharing (also called grandfathering) and economic-contribution-based-sharing approach facilitated by the availability of environmental impact estimates (eg, resource use, emission intensity) and economic data (eg, gross value added, final consumption expenditure, employment contribution).

Cross-scale translation of planetary boundaries has mostly been applied at the national level[31,338–342] and for supranational territories, such as the EU.[31,343,344] There are fewer instances of cross-scale translations to the city scale, although examples include translation of the Thriving Cities Initiative to Amsterdam[345] and downscaling of planetary boundaries to cities for 62 major cities of the Middle East and North Africa.[346] In these studies, an equal per-person allocation was used, although in some so-called hybrid approaches such as equality-sovereignty,[347] a range of shares based on multiple-sharing approaches (ie, capability, right to development, needs, and sovereignty) were used.[31]

Cross-scale translation of planetary boundaries to sectors and companies is primarily applied in two ways. First, translation of a global budget goes through the country or supranational territory, from where the country's budget is further distributed to sectors within the territory and then to businesses within each sector.[348–351] Second, the global budget is assigned directly to the studied sector within a country in proportion to its global share of the relevant impact.[352,353] These studies on cross-scale translation to sectors and companies combine different sharing approaches, most commonly the equality-sharing approach with the legacy approach,[348,350,354] or the equality-sharing approach with economic contribution.[334,348,354,355] A range of shares resulting from application of different approaches is typically reported to show the sensitivity of the allocated budgets to the choice of sharing approaches and to emphasise the need for methodological transparency.[354,355] For companies and cities, proper governance mechanisms around translation are crucial to avoid a situation in which actors take advantage of the lack of consensus on a universal fair sharing approach to engineer the easiest possible targets based on available sharing approaches (appendix pp 18–19).

Together with the choice of sharing approaches, environmental impacts or footprints of cities and businesses inform allocation of fair shares. These impacts or footprints can be measured using consumption-based or production-based perspectives.[30] The former includes all impacts and resource use associated with consumption of locally produced and imported products, whereby the impacts can occur anywhere worldwide at all stages of production along the products' supply chains. The latter includes impacts and resources used in the production of goods that takes place within a geographically defined boundary. These two approaches differ regarding the fundamental causes of environmental impacts, and in terms of with whom the final responsibility of such impacts lie—ie, the consumer or the producer. A consumption-based approach can help to allocate shares to countries, states, cities, and households, although this needs to be combined with production-based approaches for cities with heavy industrial bases. For industrial sectors and companies, shares can be allocated based on their production impacts, whereby both direct impacts (ie, scope 1: impacts from business operations at own sites and facilities), indirect impacts (ie, scope 2: impacts associated with purchases of goods and electricity as factor inputs), and other broader indirect impacts (ie, scope 3: impacts from upstream and downstream of the company's value chains) should be considered.

Although there is an urgent need to connect ESBs to cities and companies, there are also challenges. In the next sections, we articulate these challenges and suggest pathways to overcome them at sub-national scales to begin charting a path towards the safe and just corridor.

### Challenges of translation for cities

Translation studies for cities are oriented towards population-based allocations and comparative environmental footprints arising from consumption and production.[30,346,349,356] However, the choice of resource allocation methods influences the translated results. A city with high per-person consumption but low concentration of production activities might have a high consumption footprint relative to its production footprint and vice versa. Reconciliation of these translation approaches is challenging, and thus it is desirable to calculate both production and consumption footprints.

Adoption of various environmental and sustainability targets is a common practice in many cities.[319,357–359] Despite cities often having limited institutional and financial capabilities,[360] there is a compelling economic case for them to act on issues such as climate change.[361] However, city-level targets (eg, net-zero carbon-emission targets) are likely to be voluntary, aspirational goals that do not add up towards absolute sustainability at planetary level. Many more cities globally need to adopt binding targets, with real material commitments that cover all ESB domains to enable life within the safe and just corridor.[294]

Translation of ESBs for cities also needs to consider urban dynamics (ie, growth and shrinkage of cities), natural and ecological endowments and pressures (eg, climatic conditions, proximity to sensitive habitats, levels of water stress), the socioeconomic context, and existing challenges and capabilities (eg, adaptive capacity). Increases in economic activity, urban population[362] and resource use,[363] and municipal service levels can increase pressures on ESBs. Thus, allocation strategies should account for cities' ecological endowments and vulnerabilities, socioeconomic context in terms of human wellbeing and security, and institutional and governance capacity. To do so, adjustments are required to the initially allocated shares of resources and responsibilities to different cities, while ensuring the aggregated total still remains within the ESB (which is essential to meet the justice considerations we outlined).[81]

### Challenges of translation for businesses

Translation of ESBs to businesses presents challenges stemming from their highly heterogeneous and dynamic nature, their complex interrelationships with other businesses and policy makers across supply chains and geographic locations, and constraints surrounding corporate disclosure of essential information. Many businesses operate across multiple jurisdictions and have substantial environmental impacts beyond the countries where they operate.[302] Moreover, limited information exchange between scientific researchers and businesses has constrained definition of ESBs in actionable terms—eg, in relation to calculating and reporting a company's biodiversity footprint.[364] The business-specific information required for cross-scale translation is often available only for larger companies and fragmented in scope. This lack of comprehensive, consistent, and comparable business-specific data, coupled with complex supply chains, further complicates translation of ESBs to individual businesses. Finally, conceptualising the Earth-system impacts of a business in relation to consumers living in a specific area (such as a city) to avoid double counting is challenging. However, when allocating responsibilities, double counting is less problematic, given that most ESBs are already transgressed, and could help to accelerate reaching the safe and just corridor.[291]

Many businesses are adopting science-based targets for climate change,[313] and there is an increasing call for companies to start setting science-based targets for freshwater.[365] These targets require companies to account for both their direct impacts and their impacts and dependencies across the value chain.[332] Many businesses are also increasingly looking into addressing their scope 3 emissions.[366] Initiatives to align corporate actions with global goals, such as the Paris Agreement, rely primarily on voluntary engagements,[367] with each participating business setting its own targets (appendix pp 18–21), although the EU Emissions Trading System is a notable exception. Businesses are also assessing the material risks to their future financial performance posed by environmental change, triggered by initiatives such as the Task Force on Climate-related Financial Disclosures and the Taskforce on Nature-related Financial Disclosures. Both of these taskforces have developed and produced recommendations for businesses to disclose information on climate-related and nature-related impacts, dependencies, risks and opportunities in consultation with representatives of financial institutions, large corporations, accounting and consultancy firms, and credit ratings agencies.[368,369] For decades, companies have reported their performance on their financial bottom lines and their environmental and social impacts and responsibilities as part of assessing and managing risks to profitability and sustainability. However, such voluntary initiatives often are insufficient to achieve global goals.[294,370]

For more on the **Task Force on Climate-related Financial Disclosures** see https://www.fsb-tcfd.org/

For more on the **Taskforce on Nature-related Financial Disclosures** see https://tnfd.global/

Organisations such as the World Business Council for Sustainable Development are developing practical tools and a data roadmap to enable companies to account for scope 3 emissions.[371,372] These tools could help to encourage wider engagement with company-specific impacts. Allocation of resource budgets and mitigation responsibilities can be undertaken using the environmental impacts (as measured via production footprints), with post-allocation adjustments that account for the socioeconomic contexts of the business.[81] Such an approach enables incorporation of the triple bottom lines (ie, financial, social, and environmental) into translation and the positioning of businesses within the wider socio-ecological-economic system.

Allocation of responsibility for reducing environmental impacts could be effective, but could overlook actors with low direct impacts but substantial opportunities to shape the environmental behaviour of others—eg, financial institutions, which are not prominently featured in translation efforts focused on direct environmental impacts, but can enable or obstruct efforts by businesses to set and meet targets.[373] Many businesses require continued investment in green innovation to remain competitive.[374] To attract investment, businesses need to show solid financial performance, low environmental impacts, and social acceptability. Investors, banks, and other financial actors seeking to minimise their risk exposures to climate and ecosystem change[375] can facilitate divestments from fossil fuels or high-impact production to alternative, greener, low-impact production.[376] Although such divestment could create new vested interests, financial institutions have the potential to accelerate societal transformation towards a safe and just corridor.

## Translation of safe and just ESBs for cities and businesses

For cross-scale translation to be adopted, methods and strategies need to adhere to broadly acceptable common principles. Ten principles[81] for translation and subsequent target setting have been identified to facilitate best practices: translation approaches and applications should be scientifically rigorous, transparent, just, systemic, sufficiently safe, and context sensitive, and science-based targets (ie, based on the outcomes of translation) should be enabling, incentivising, dynamic and time bound, and synergetic.[81]

For cross-scale translation to be scientifically rigorous, the methods should be consistent, reproducible, and transparent. Figure 23 shows key steps for translation of the ESBs to cities and businesses, and how translation is linked to the attribution of environmental pressures exerted by city inhabitants and businesses. Translation is a two-step sequential process of transcription, followed by allocation and adjustment.

The first step is to transcribe the state indicators used to quantify the safe and just ESBs into units that can be linked to actors—ie, converting ESBs into flow or pressure indicators related to relevant causal chains (eg, conversion of the degrees of global warming to tonnes of carbon dioxide emissions, conversion of surface water flows to megalitres of water extracted). This conversion allows ESB state variables to be transcribed into resource budgets and abatement responsibilities, that is budgets of water, nutrients, land, carbon, and particulate matter that can be safely used or discharged to the environment. These budgets are expressed in the same units as the measured environmental footprints or pressures emanating from cities and businesses.

The second step is to allocate the transcribed budgets to actors. Allocation involves the downscaling of either maximum available aggregated pressures associated with ESBs that have not yet been transgressed (ie, resource budgets), or, for transgressed boundaries (eg, climate change), minimum associated mitigation and abatement responsibilities to the target level territories and entities.[334] It could involve allocation to the smallest unit (eg, an individual person or land unit) appropriate for the ESB (figure 24), followed by aggregation per unit budget to target level. Countries and industrial sectors are intermediaries (or intermediate points) in the translation to businesses (figure 24; appendix pp 23–24).

After cross-scale allocation comes adjustment, which seeks to redistribute these initial allocated shares between actors within the same scale (ie, between cities, countries, sectors in a country, and businesses within a sector; figure 24; appendix pp 22–23) to account for differences in their social, economic, and ecological contexts. Current and projected production and consumption footprints of cities and businesses could be an important ecological context to consider in these steps. Further adjustments might also be needed before

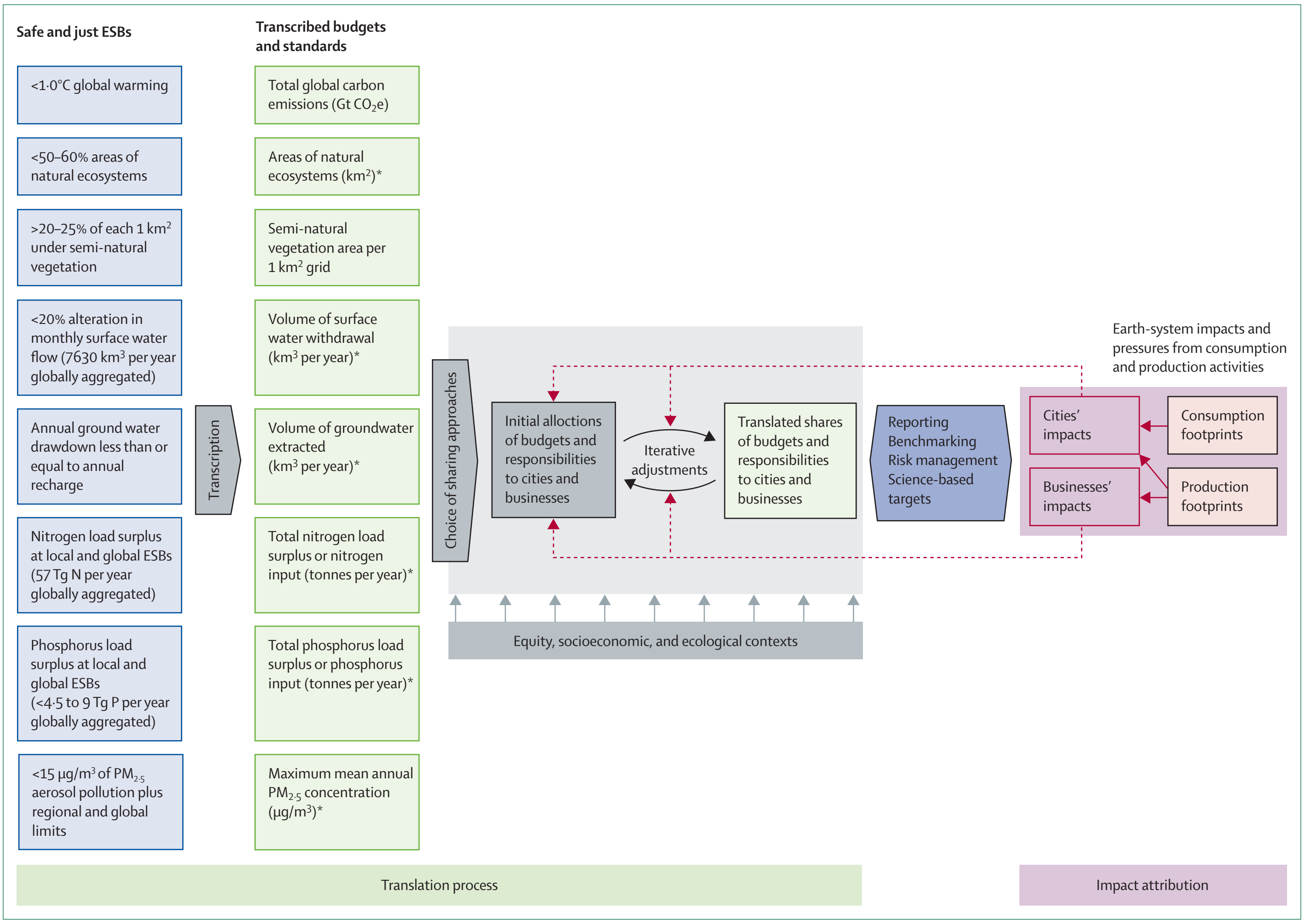

*Figure 23:* **Steps for translating ESBs to cities and businesses, and attribution of impacts exerted by urban inhabitants and businesses**

Equity-related, socioeconomic, and ecological contexts influence the choice of sharing approaches used in the allocation step and iterative adjustments. The ESBs are translated into shares for actors, which are informed by the impact assessment, and can be used for informing city-level and business-level reporting, benchmarking, risk management, and science-based target setting. $CO_2e$=carbon dioxide equivalents. ESBs=Earth-system boundaries. *Transcribed budgets and standards that are spatially specific and whose aggregation produces the global quantities.

connecting the ESB shares to policy targets, because resource capacities could change through metacoupling (ie, human–nature interactions within a place, between adjacent places, and between distant places in the world),[377] such as inter-basin water transfer[132,378] or technological means such as desalination of sea water or carbon capture and storage.[379–381]

Allocation and adjustment are implemented according to sharing approaches, reflecting different aspects of justice, and are enacted according to a metric dataset that is harmonised at the appropriate scale. The appendix (pp 16–17) shows examples of commonly used sharing approaches and enacting metrics, including the relevance and potential of these metrics to address the Earth-system justice principles.

For ESBs with a regional budget (based on global and sub-global ESBs),[10] translation could follow a global citizen approach—ie, sharing the global budget equally among the entire global population—or could follow a bioregional approach, whereby a regional budget is shared equitably within a region.[81] Application of a bioregional approach alone has several limitations, as a result of the increasingly intertwined, complex, and global production and consumption systems that mean that actions have impacts beyond specific regions, the mismatched distribution of resource endowment and population concentration, and the mismatched distribution of responsibilities and benefits.[81] Thus, bioregional approaches need to be benchmarked against a global citizen approach.

## Translation of specific ESBs for cities and businesses

### *Biosphere*

The ESB for natural ecosystem areas recognises each ecoregion in terms of NCP. The pressures degrading the ecoregions are globally distributed through

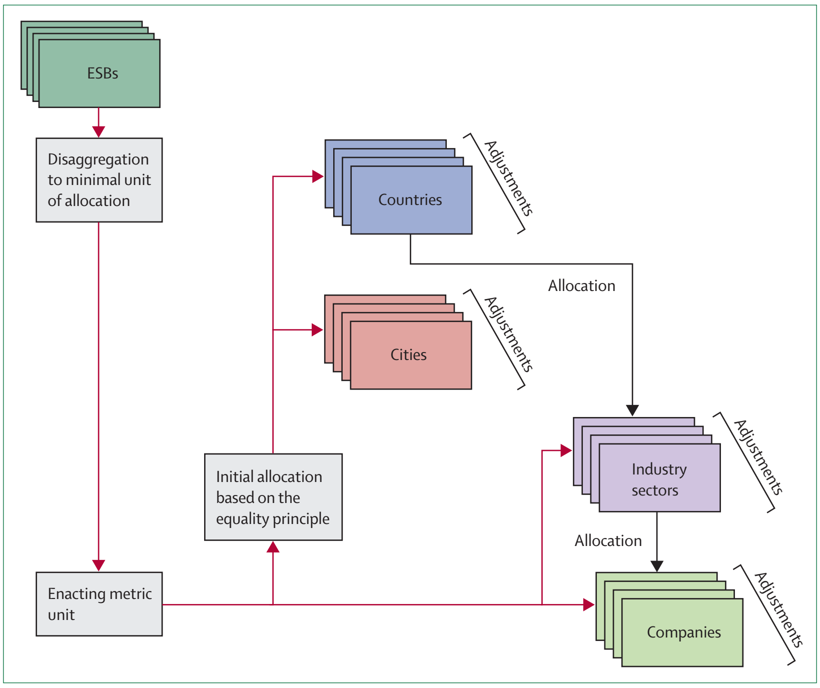

*Figure 24:* **Example of allocations and adjustments for translating global and sub-global boundaries**
This example builds on the work of Hjalsted et al, 2021,[334] and Suàrez-Eiroa et al, 2022,[349] and uses the equality principle as a starting point. Available budgets or responsibilities are first disaggregated to the smallest unit allocation (eg, an individual person for carbon dioxide equivalents and water use, a hectare of agricultural land for nitrogen and phosphorus), and then this per-unit budget is aggregated to higher-level entities or agents (eg, countries, cities, sectors, companies). The appendix (pp 23–24) includes corresponding generalised mathematical expressions for allocation of resource budget and responsibilities to cities and businesses, with countries and sectors as intermediate points in allocation to businesses.

production and consumption systems. Halting further loss of nature and restoring degraded ecoregions is important locally and globally.

This ESB could be translated via a global commons perspective, in which the natural ecosystem area target for all ecoregions and the costs of delivering the targets are shared by all actors worldwide (ie, shared responsibility of a global commons). Alternative approaches include a bioregionalism perspective, in which the target for the largely intact natural area of a specific ecoregion and the associated costs are allocated locally (local responsibility), or a consumption and production footprint perspective, whereby a natural ecosystem area target is allocated to actors responsible for exerting pressure on that ecoregion, irrespective of where they are located. For example, the ESB could be transcribed to manageable pressure indicators based on the agricultural land footprint of production and consumption activities,[382–384] given that the expansion of agricultural land is a key driver of biodiversity loss.[5]

In the absence of a global governance body, the biosphere ESBs could be operationalised through local government or by actors incentivised to reduce their pressure in critical ecoregions to meet the expectations of consumers and investors. For example, cities and businesses could limit and redress their respective consumption and production footprints in critical ecoregions and report on this process.

The safe ESB for functional integrity is a minimum of 20–25% natural or semi-natural habitat per km² of human-modified lands. This boundary can directly be used by local authorities to guide land zoning, restoration, prioritisation of investments on land and catchment to improve delivery of NCP to local communities, regulations on residual discharges, and strategic plantings and conservation areas on farms to support and deliver optimal biodiversity outcomes. Because this ESB is already expressed at a fine grid scale (1 km²), it does not need to be translated.

### *Climate*

As of 2023, the long-term global warming trend had passed 1·2°C (ie, the just climate ESB of 1°C has been exceeded),[385] and thus cumulative global carbon dioxide, methane, and nitrous oxide emissions need to be curtailed. This target can be transcribed to an annual budget of gigatonnes of carbon dioxide equivalents ($CO_2e$). Currently, there is no established $CO_2e$ budget on a global scale that corresponds to the just ESB of 1·0°C. Thus, to exemplify the translation of the climate ESB, we use the existing $CO_2e$ budget associated with a global warming limit of 1·5°C.

The IPCC's sixth assessment report[140] aligns a remaining carbon budget of 500 gigatonnes of carbon dioxide from the beginning of 2020 onwards, with a 50% chance of limiting global warming to 1·5°C. Translation of this target implies allocating the budget to actors annually for a given time horizon. As the actor-specific allocated budget is less than the amount of current emissions, carbon abatement and mitigation will need to be undertaken, including through a so-called global carbon law reduction pathway of halving gross anthropogenic emissions every 10 years for all sectors and countries[386] or equal annual emissions reduction (ie, carbon emissions are reduced by a fixed amount each year). Allocation of a carbon budget is contentious, with different actors advocating for different sharing approaches, including those mediated by carbon markets. However, these annual budgets can be allocated on an equal per-person basis in the first instance to express the average global citizen emission share, which can provide a reference point for immediate actions.

### *Nutrient cycles*

The global ESBs for nitrogen and phosphorus can be allocated per land unit (ie, per hectare of agricultural area, given that agriculture contributes roughly 90% of anthropogenic nitrogen and phosphorus inputs) or per person (because the main driver of surplus nitrogen and phosphorus is consumptive demands for food production). The sub-global ESBs for nitrogen and phosphorus are based on flow criteria and concentration limits, which can be allocated regionally (again by area or per person). Targets should ensure that local concentrations of nitrogen or phosphorus in water do not exceed local boundaries. Target actions could focus on reducing food waste, improving sewage and wastewater quality, and reducing nitrogen and phosphorus footprints associated with food sourcing via dietary change.

### *Blue water*

The monthly surface alteration budget of a given basin (ie, no more than 20% of prevailing natural flow patterns) can be allocated per person and aggregated to show boundaries at a city level, symbolising the maximum consumption of the average global citizen that should be adhered to stay within the ESB. The transcription of the basin-scale ESB requires an assessment of monthly flow alteration in surface waters. Where local-scale environmental flow requirements have been established by flow-ecology analyses, these targets should be used to define safe and just levels of flow alteration for a given watershed.

The groundwater ESB is a regional boundary expressed such that annual extraction from a given aquifer should not exceed its annual replenishment rates. The global budget can be allocated equally per person to express the average global citizen share. For regional boundaries, extraction should be limited within the recharge level.

Translation of water ESBs to cities and businesses should consider surface and groundwater together. Water budgets should then be allocated to competing uses: municipal, industrial, rural, and agricultural. It can be assumed that water demand is relatively constant for cities and businesses compared with the fluctuating demands in agricultural contexts, but all these actors share responsibility for the water flow system. The allocation process should consider the interlinkages between upstream and downstream water use and flow alteration, and how actions in hydrologically connected regions will collectively affect recharging of aquifers. For businesses, the water use for production can be established in relation to the water availability at the locations of withdrawal of surface and groundwater. The resulting water footprint can be used to identify regional hotspots of water overuse within production chains[387] and thus help to approach the water ESBs.

### *Aerosols and air pollution*

To operationalise the aerosol ESB, the annual limit of 15 μg/m³ $PM_{2·5}$ needs to be converted into annual maximum allowable loads (by weight) based on information about flow rates. Data for $PM_{2·5}$ concentrations and flow rates can be obtained from end-of-pipe (for industrial sources) monitoring points and strategically placed sensors (eg, in urban areas). Given that $PM_{2·5}$ is highly place and source specific,[10] translation of this ESB involves allocation of spatially specific loads of $PM_{2·5}$ to industrial and non-industrial sources situated within the relevant areas. The final translated share has health implications locally and regionally, and thus health outcomes should be embedded in the selection of sharing approaches alongside socioeconomic and ecological concerns.[388] Health professionals also need to be included as important stakeholders in the subsequent setting of science-based targets.

## Earth-system justice in translation

Although translation scholarship discusses the link between sharing approaches and distributive justice,[30,334,335] this link is rarely made in the literature about translations to cities and businesses. Instead, researchers often invoke principles that relate to value creation of businesses,[336,337] without making explicit the link between allocation approaches, fairness norms, and health outcomes. Although urban translations often invoke the equality principle because it is considered objectively fair that everyone is equally entitled to Earth's resources, translation efforts that seek to address justice need to take further steps and account for the underlying complexities and differences in the environmental and socioeconomic contexts of actors across different scales.

No translation method is perfect or without uncertainty, and no one method can address all the nuances of on-the-ground situations and justice. Likewise, no single sharing approach can address all aspects of distributional justice at once, and coverage varies between the five domains covered by the ESBs and whether justice involves reallocation of available resources or impact reduction responsibilities. For example, we argue that economic-contribution and legacy-sharing approaches can enable intragenerational justice in terms of allocating responsibilities for reducing environmental pressures but not for allocating available resources such as water (appendix pp 18–19). Sharing approaches based on meeting basic human needs could help to achieve intergenerational and intragenerational justice for both resource and responsibility allocations. As each sharing approach reflects a particular perspective of fairness, cross-scale translation often requires an iterative process of allocation and adjustment (figures 23, 24) to accommodate competing and complementary interpretations of distributive fairness.

There are risks inherent in an approach that accommodates multiple interpretations of fairness. Powerful actors could use this flexibility to lobby for a translation approach that benefits them. Hence, translation approaches need to be embedded in rigorous governance systems with a focus on Earth-systems justice. Transparency is a crucial element of governance. To ensure transparency, cities and companies should disclose all their translation steps and justify all the choices made along the way, so that third parties can scrutinise these choices. Such a transparency requirement, although modest, is not in place for corporate science-based targets for greenhouse gas emissions, thus hampering their effectiveness.[389]

The methodological difficulties of translation are a challenge for operationalisation of ESBs for cities and businesses. Cities and businesses have enormous potential to contribute to moving within the safe and just corridor, but cannot act alone. Cities are embedded within broader socioeconomic, environmental, and institutional structures.[390] Businesses are intrinsically connected to, and influenced and constrained by, actors across their supply chains and throughout their product lifecycle.[294] Structural changes—eg, creation of national and international regulatory frameworks, incentive structures, and enabling policies—are essential.[391] Consumer choices and public opinion can also influence businesses, including the types of products made and how they are produced, and what technologies should or should not be invested upon. Change of norms, values, and world views are necessary for respecting Earth-system justice and the safe and just ESBs, and stronger adherence to justice principles is needed in cross-scale translation for intra-sectoral or cross-sectoral adjustments to be successful. The communications sectors, including traditional and social media and advertising companies, among others, are major cultural value creators. Although these actors often have relatively small footprints, the value they create and perpetuate can have large Earth-system impacts. Technological change could alter resource-use efficiency and the intensity of environmental impacts, which could in turn change the allocated shares across cities and businesses.

To effectively mobilise cities and companies to respect their fair share of responsibilities will probably require nothing less than a broader societal transformation. Businesses and cities are just two of the important actors that can contribute to the systemic transformations needed to move within a safe and just corridor. In Part 4, we review the growing literature on the need for Earth-system transformation and identify major transformations in consumption, technology, economies, and governance.

## Part 4: Transformations for a safe and just planetary future

The speed and intensity of harmful Earth-system changes mean that conventional solutions are inadequate to live within the safe and just corridor. Fundamental system-wide transformations are needed to remain within the ESBs, ensure wellbeing, and provide equitable access and allocation of resources.[32,392]

Transformations are more profound and comprehensive processes of change than transitions.[393] Transitions tend to focus on reducing direct pressures on the environment in key sectors (eg, energy, food)—and on incremental changes in behaviour, technologies, and policy. Transformations, by contrast, involve systemic, synergistic, structural, political, practical, and individual changes across scales to address fundamental drivers of Earth-system change.[32,392,394–396]

For example, environmental historians record key transformations that changed human impacts on the natural environment, including the domestication of plants and animals, European colonialism, and the industrial revolution.[397] Although agriculture and industrialisation improved health and wellbeing, they also led to biodiversity loss, land-use change, pollution, and the dispossession of Indigenous peoples. Thus, transformations can be both positive and negative. Colonialism, in particular, left a legacy of inequality through which many countries became a source of wealth and resources for European elites via slavery, mining, agricultural exports, and exploitation of land and workers.[398–401] These inequalities persist, with powerful countries and companies in Europe and North America continuing to control trade, finance flows, land, and labour and extracting value from poorer countries and peoples.[402]

World War 2 brought rapid political, technological, and governance transformations after 1945, including expanded use of chemicals and pharmaceuticals, the Cold War, the development of nuclear power and nuclear weapons, a more globalised economic system, the formation of the UN, and growth in consumption and population, often termed the great acceleration.[403] From the 1970s, growing awareness of environmental degradation led to the environmental movement, UN environmental action, stronger non-governmental organisations, environmental education, and international health and environmental regulations. Important demographic transformations since 1950 include rapid global urbanisation (from 30% to 56% in 2020)[291,404] and a halving of fertility rates, slowing population growth. Justice-based transformations include the abolition of state-sanctioned slavery in many regions and of state-sponsored apartheid in South Africa, and a more widespread recognition of human rights, including those of women.[405]

Transformations can be initiated by positive social tipping points that can result from the spread of new norms and behaviours, the rapid drop of prices for sustainable technologies, or profound shifts in governance regimes.[405–415] Scholars of sociotechnical[410] and socioecological systems[49,416] emphasise cross-scale and multiphase dynamics whereby changes in beliefs, technology, behaviour, or sustainability institutions expand in scale from niches through regime to landscapes. The transformations towards sustainability in energy, food, and urban systems that we outline later in this Part include several examples of such social or socioecological tipping points.[417,418]

Systemic and structural transformations to move into the safe and just corridor need to address fundamental drivers of Earth-system degradation and vulnerability.[419] If transformations are to address these drivers, they should address who uses resources, how, why, where, and when they use them, and who has power to alter decisions and the environment.[420] Assessments that summarise fundamental or indirect drivers most often include population, consumption, technology, values, information, and economic development and contrast these drivers with direct or proximate drivers, such as land-use change, urbanisation, energy use, infrastructure extension, and agricultural expansion.[421] Frameworks conceptualising drivers include the Ehrlich–Holdren identity and the IPAT (ie, impact=population + affluence + technology) formulation, which assumes that population, affluence, and technology determine environmental impacts,[422,423] and the DPSIR (drivers, pressures, states, impacts, and responses) approach, which identifies, for example, population and economic development as drivers.[424,425] Integrated assessment models usually use some combination of population, technology, resource availability, environmental constraints, and economic development as drivers of scenarios[426] but pay inadequate attention to moral and social values, inequality, and alternative growth policies.[427,428]

Critical scholars argue that capitalist political and economic systems are the drivers that need to be transformed to ensure a stable Earth system and social justice. They link these drivers to the exploitation of both people and nature, and argue that they create inequality and environmental degradation via a focus on profit and accumulation.[429–432] These scholars also argue that colonial political and economic processes dispossessed local and Indigenous peoples, changed land use and exacerbated global inequalities that persist under both democratic and autocratic governments.[433–436] Recent neoliberal processes of reduced government, free trade, and privatisation of the commons are blamed for undermining public services and environmental protection.[437–439] In both democracies and autocracies, powerful elites oppose transformative policies that redistribute wealth and protect the environment.[440,441] However, state authorities can intervene against elite interests in response to social protest and when environmental crises or health emergencies undermine profits.[442,443]

Critical scholars highlight the risks of trade-offs, and of discourses that justify business as usual, assume consensus, ignore equity and human rights, shift the burden of action from those most responsible for degradation to less well-off countries that are not responsible for problems, and demand action from the individuals and groups most affected by yet who contributed least to environmental degradation.[437,444,445] Many barriers to transformations that lock in business as usual or limit the scale of change have been identified. For example, legal barriers include long-term and confidential contracts between governments and investors that guarantee access to resources such as energy, land, and water without attention to environmental protection.[446] Property rights can be used to challenge regulation and convert common lands to private ownership.[447] Legal remedies are few when people and nature are unable to obtain recognition in the form of legal standing in courts.[448] Political and institutional barriers include the fragilities of multilateralism,[449] the erosion of democracy,[450] and the loss of multiparty compromise. In many countries short-term political cycles and polarisation of social and environmental issues are slowing or reversing change.[451] In others the persistence of autocracy and powerful elites exclude many people from decision making, control elections, repress unions, and punish protest.[450] Institutional rules and cultures[71] also prevent fundamental change, and although it is possible for all forms of government, from representative democracies to dictatorships, to enact some change, not all do so in inclusive ways.[451]

International environmental assessments increasingly call for just, systemic transformations and transitions.[48,120,121,140,452,453] Most of these assessments prioritise reducing poverty and inequality, and focus on transforming energy, food, health, and urban systems; reducing consumption by adjusting values, lifestyles, and perceptions of success; changing political and economic systems to be more inclusive; challenging powerful interests; and incentivising sustainability.[454,455] Proposals for just transitions call for expansion of decent, green, and just jobs (with fair wages and healthy working conditions in industries advancing sustainable resource use), social protections including health care and food security, circular economies, widespread access to and participation in decision making, and recognition of the rights of communities and Indigenous peoples.[456,457] Calls for transformations appear in multiple forms and terminologies, including calls for alternative pathways such as degrowth, inclusive development, buen vivir, ubuntu, and green new deals.[458–461] Calls for transformation are also grounded in improved health conditions. For example, the Alma-Ata Declaration asserts that health for all is a universal human right, achieved in part through universal access, equity, participation, and intersectoral action, as well as healthy environments.[462]

Social barriers include poor availability of accessible, independent, or unbiased information and knowledge systems.[463] Marketing that promotes consumption; a distrust of science and public institutions; and cultures, social norms, values, and habits or beliefs that resist or take time to change are other barriers.[464–466] Economic, technological, and infrastructural barriers to transformation include assumptions about what constitutes progress (eg, gross domestic product metrics),[467] discounting the future,[468] devaluing poor or marginalised people, and ignoring environmental and health externalities in pricing goods. Other barriers include the problem of stranded resources, investments, and assets[469] including fossil fuel energy and unsustainable urban design, and technological and infrastructural lock-in and lack of investment to overcome it.

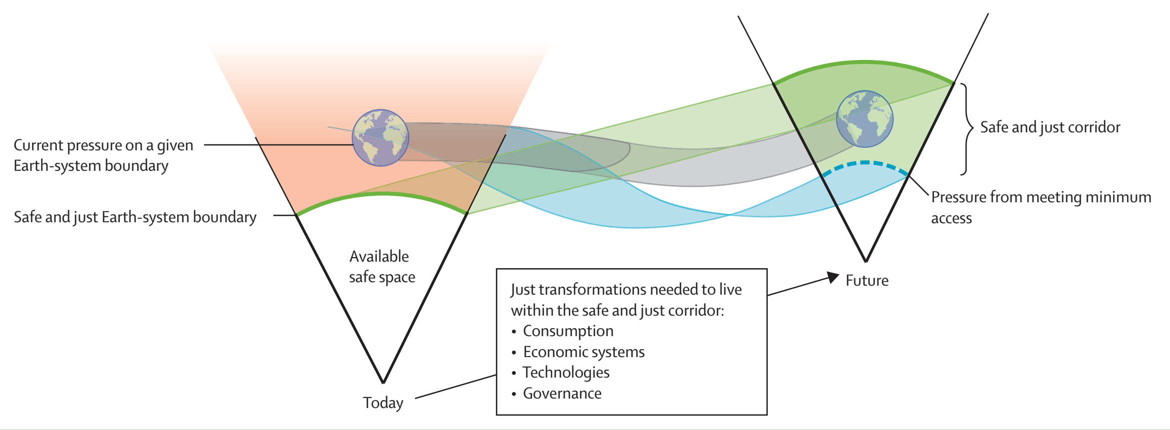

**Figure 25: Transformations required to enable life within the safe and just corridor**
Most of the safe and just Earth-system boundaries have already been transgressed, and many people do not have minimum access to food, water, energy, and infrastructure. Thus, inter-related just transformations are needed to address consumption, economic systems, and technologies, and to achieve overarching transformations in systems of governance across scales.

## The portfolio for transformations

Our transformations portfolio looks to address the ends and means needed to live within the safe and just corridor (figure 25). The end goals are to reduce significant harm through reducing pressure on ESBs and to ensure minimum access to resources for those without adequate access. The means to enable these goals to be achieved include inclusive decision making, recognition of the people and regions most affected, and the redistribution of the remaining resources and responsibilities through equitable transformations of consumption, economic systems, technologies, and governance. The proposals we make are consistent with the spirit of the SDGs.

Just transformations need to address multi-level injustices, corporate responsibility for pressures on the Earth system, and the deep vulnerabilities of poor and marginalised people.[470] Relative and absolute income and wealth inequality are increasing,[471,472] and environmental degradation is mostly caused by a small but affluent proportion of people, who mostly live in high-income countries.[18,473,474] Hickel, for example, argues that emission-reduction scenarios do not address the need for high-income countries to cut emissions steeply because of their historical responsibility, greater capacity, and higher incomes, and documents the inequities in other resource consumption reflecting colonial legacies.[400,475–477] Disproportionate responsibility is also apparent among business actors, with 100 corporations emitting 71% of global carbon dioxide emissions.[478]

Access to information is a cross-cutting priority in transformations. Science can be transformative through theory and practice that focuses on minimising Earth-system risks and injustice, including through staying within safe and just ESBs.[10,294] Epistemic justice requires the use of different knowledge systems, processes, and indicators, including Indigenous and local knowledge, to enable transformations.[479] Transformations can be autonomous or deliberately initiated, implemented, spread, or resisted by different actors.[480] There is a continuum of interactions across individual, organisational, and system-wide transformations.[481] We propose four fundamental and interrelated transformations supported by system-wide changes in governance (figure 25), including reducing and reallocating consumption, transforming economic systems, and expanding access to sustainable technology.[451]

### *Reducing and reallocating consumption while ensuring minimum access*

Reductions in excess consumption and reallocation of consumption to people without adequate access to resources is needed to live within ESBs and is increasingly recognised as a transformation priority aligned with distributive justice.[140] Individual decision makers in households, companies, and governments have agency to change values, structures, and behaviour to reduce consumption. Consumption through everyday demand for products and services per person is a key driver of Earth-system change as fertility rates decline and population growth slows.[482]

Overall population patterns contribute to pressures on Earth systems. Improvements in gender equality, education access, women's status, health care, urbanisation, education, and income levels have resulted in rapidly declining fertility,[483] which are projected to reverse population growth. Improving women's rights could reduce overall consumption and has already resulted in a social tipping point towards sustainability, while making women less vulnerable to climate change.[484]

Average consumption per person has increased substantially since 1970 (energy consumption has increased by around 35%, and food consumption by around 25%).[485] Some increases are associated with declining poverty, but wealthy countries and individuals consume disproportionately more because social norms, media, and advertising promote consumption in terms of large homes, automobiles, and frequent air travel.[13,400,472,486] The lifestyles and consumption patterns of the elite, which are over-represented in media, influence the social norms and aspirations of the growing middle classes who sometimes then emulate upper-class consumption styles.[487,488] Transformations can be guided by sufficientarian principles, which ensure minimum access to resources and an upper limit to prevent excess consumption.[489]

Changes in consumption have complex causes that are associated with both individual behaviour and structural forces. Increases in consumption are associated with rising income, falling costs, marketing, planned product obsolescence, dietary choices, and socio-psychological factors,[490] whereas decreases are linked with conservation values, rising costs, and government policies that reduce overconsumption or support sustainable choices.[491–493]

Changes in values underpin changes in consumption behaviour of individuals, policy makers, and corporate leadership. Shifting social norms and cultural values can stimulate politicians to enact ambitious environmental policies.[494] Information and knowledge systems can drive transformations in consumption through education, public awareness, cultural visions, setting of targets, monitoring and reporting of environmental impacts and compliance, and genuine green marketing.[495–497] Information can overcome barriers including misperception and unwillingness to support policy changes or adopt new technologies. Communicating alternative worldviews and norms can trigger behavioural changes.[498] However, the media, especially when aligned with political parties or corporations, can bias, ignore, or promote information that influences the public. Affluent elites have the agency and ability to shape social norms and institutions.[499] Social norms are the basis of law.[500] Therefore, recognition of the immoral character of fossil fuels, for example, can lead to regulations restricting fossil fuel use and introducing advertising bans.[501]

Limitarian justice principles suggest limits to wealth[489] and consumption of resources.[502,503] The disproportionate environmental impact of luxury and wasteful consumption[17,473,504] is addressed in post-growth and degrowth scholarship, which emphasises the need for a drastic shift to basic, necessary, sustainable, or satisfying consumption.[505–508] Consumption and travel that emphasises the quality of individual and collective lives is preferred to that which satisfies social norms or artificially created needs and desires that are continuously reinvented by advertising firms to push growth.[509] Limiting what is possible for some people allows the opening up of possibilities for others.[510] Research that links energy consumption with social provisioning suggests that wellbeing does not increase much above a modest level of energy consumption. Per-capita consumption is often lower in systems that prioritise public services, income equality, democracy, and public health.[511] Demand-side solutions in climate mitigation not only have the potential to reduce counterfactual sectoral emissions by 40–80% in end-use sectors, they also have largely positive effects on human wellbeing.[512]

There are many accepted and effective mechanisms for reducing and reallocating the consumption of high-income consumers—eg, interventions such as provision of environmental information, peers sharing their sustainable actions, progressive and enforceable taxation, graduated resource pricing, land-use planning, green technologies, and subsidies for more sustainable options.[140] Innovations in public communication institutions and boundary organisations that connect science with communities can incorporate other knowledge and values (eg, local and Indigenous knowledge), enhance transformative capacities, reinforce positive feedbacks, and trigger sustainability learning.[513–515] Socio-technical transformations can be supported by standards, certificates, labels, bans on advertisements for harmful products,[516] and campaigns to change household behaviours. Information and pricing can reduce waste, air travel, and meat and dairy consumption.[486]

Legal strategies can reallocate consumption and waste by using consumer, environmental, international, and constitutional law.[517] However, reducing and reallocating environmentally important consumption is challenged by growth-oriented political and economic systems and by the lack of affordable sustainable choices for consumers.[518]

### *Transformations of economic systems for sustainability and justice*

Unequal and excessive personal consumption is rooted in economic systems. Pollution costs are externalised in the cost of products and services. Trillions of dollars are invested in fossil fuels and mineral extraction, and shifts to lower-carbon energy systems are undermined by the risk of stranded assets and powerful interests.[519,520] Investments using accumulated wealth often involve land and resource grabs and protection of these investments against claims that they do not adhere to environment, social, and governance criteria or use of socially responsible investment tools.[521]

The environmental impacts of economic growth and growing inequality can be addressed through policies that require external costs to be included in prices, that measure progress through alternative indicators, that mandate decent working conditions and pay, and that monitor and control investment, subsidies, and trade. The financial system can be transformed through reporting of environmental risks, scaling up of private and public finance for environmental protection, providing access to resources and credit for poor people and countries, and avoiding harmful subsidies and investment. Cancelling debt, limiting structural adjustment policies that cut public spending on health and environment, offering grants rather than loans, and ensuring low interest rates for sustainable activities can enable transformation in low-income countries and remedy historical inequalities associated with unequal exchange.

Economic transformations could provide effective means to reduce pressures on the Earth system while ensuring just access. Taxation could help to reallocate wealth and profits and generate revenue for government action, but is inadequate or poorly enforced in both rich and poor countries. Tax justice refers to policies that address extreme inequality while generating the resources for states to provide public services,[522,523] and includes addressing tax havens,[524] tax evasion,[525] tax avoidance and other abuses of the tax system,[526] criminal activities, and financial secrecy.[527] Financial globalisation has enabled the rapid movement of money from one jurisdiction to another, and trade or currency exchange could be taxed to fund green policies.[528,529] A functioning tax system provides revenues to fund public services and the redistribution of wealth to curb inequalities.[522] Tax injustice reduces resources for states to finance much-needed public and merit goods (such as food credits) and environmental protection, and perpetuates inequalities.[527]

A key problem is stranded resources and assets associated with prematurely retiring fossil-fuel facilities, which mean that elimination of fossil fuels is opposed by powerful interests.[530,531] The fossil-fuel sector is estimated to be worth up to US$295 trillion.[532] To ensure global warming of no more than 1·5°C, remaining coal, gas, and oil deposits have to be left underground.[533] Most fossil fuel reserves are in low-income and middle-income countries; and some of these countries are being shamed or persuaded by international agreements and non-governmental organisations not to use these resources, while high-income governments and investors continue to invest in fossil fuels in these settings, raising multiple justice issues.[534,535] Many countries depend on the revenues from, and employment in, the fossil-fuel sector and have lobbies preventing phase out of fossil fuels despite growing social movements calling for a fossil fuel non-proliferation treaty.[501,534,536]

Perverse fossil-fuel subsidies[537] and unsustainable food systems[538] could be replaced by time-limited subsidies or incentives for sustainable alternatives.[539] Efforts to internalise external production costs (such as pollution and waste) could be accelerated through the legal system, regulation, and corporate self-regulation but could be unjust if they result in increased prices, limits access for poor people, or undermines governments' abilities to guarantee low-cost basic services. Currently, the dominant economic mechanism for resource allocation is the free market, where prices might restrict or prevent access, non-market values are ignored, and the commodification of nature often fails to achieve social and environmental goals.[540] Although financial institutions can self-govern and self-regulate—via legal and managerial mechanisms including disclosure, benchmarking, divestment, engagement, and targeted investment[541]—these approaches often have limited effectiveness given the imperative to maximise returns on investments.[330]

Many economic systems manage risk through insurance. Insurance services can offer participating actors protection against the environmental harm they cause and the harm that is caused to them.[542] Insurance actors could play a transformative and justice-oriented role in deciding who they insure, how, when, and why. However, insurance can also enable societies and governments to postpone difficult decisions or to shift the responsibility to people harmed and away from those driving harm (a type of maladaptation).[543] The projected damages from, for example, extreme climate events, could break the insurance markets, which are already unavailable or unaffordable to many poor people.

The standard measure of economic success is growth measured as increase in gross domestic product or business profits, neither of which account for environmental impacts or broader human needs. Alternative measures focused on wellbeing can foster transformations of economic systems.[544–546] Another economic metric that can be a barrier to transformations is the use of discount rates, which discount the value of damage or benefits in the future at levels that undervalue intergenerational justice.[547]

### *Expanding sustainable and affordable technologies*

Technology is fundamentally implicated in the environmental impacts of production processes.[548] Grubler and colleagues[549] argue that greenhouse gas emissions can be reduced to enable adherence to limiting global warming to 1·5°C through feasible changes in energy intensity and demand. The IPCC[550] identified various technology transformations that could help to enable decarbonisation, sustainable development, and justice—including wider use of solar and wind energy, battery storage, electric vehicles, efficiency advances, building retrofits, and alternatives to cement. The unit costs of these technologies have fallen with innovation, increased consumer demand, and government support, which has allowed for more equitable, but still inadequate, access.[550] Some scenarios, such as those used by IPCC, assume investment and implementation of bioenergy with carbon capture and storage, other methods of greenhouse gas removal, and solar radiation management. However, not all technologies are safe or just and could involve trade-offs.[551] For example, there is considerable controversy about the safety and cost of geoengineering and the environmental and human rights impacts of mining rare minerals used in some low-carbon options.[552,553]

Technological transformations could enable sustainable agriculture that could protect nature and reduce emissions through efficiencies and alternatives, including Indigenous practices that reduce use of land, polluting chemicals, and water.[480] Because nutrient use is crucial in agriculture, technological solutions include reduced synthetic fertiliser use via improvements in the efficiency of fertiliser use and soil-management practices, ensuring equitable fertiliser access, supporting regenerative nutrient-conserving practices, closing nutrient loops by improving recycling of waste and sewage, and supporting the emergence of enabling socioeconomic conditions. National and international efforts are required to overcome major barriers to reducing the use of cheap fossil fuel-derived synthetic fertilisers in high-income countries and providing access to fertilisers in low-income countries.

Technological and design transformation could also help to create sustainable, safer, and just buildings, cities, and infrastructure through promoting circular economy,[554] and decreasing vulnerabilities to Earth-system changes.[555]

The precautionary principle—which emphasises caution and preventive action in the face of environmental risks and uncertainty—could minimise the introduction and use of new harmful technologies[556] and protect health. Subsidies for sustainable and adaptation technologies could help to make them affordable for all people.

### *Transforming governance across scales*

Improved governance is crucial to enable healthy living within the safe and just corridor, by enabling transformation in consumption, economics, and technology. Earth-system governance includes the formal and informal rules, rule-making systems, and actors that can prevent, mitigate, and adapt to Earth-system changes. It includes every level of government from local to global, as well as other political, economic, and social institutions, such as business and civil society.[557,558]

Types of actors who can influence transformations include state and non-state actors, including business leaders, non-governmental organisations, and communities.[417] Counter-actors that work against a safe and just future can limit positive change. The UN Agenda 21 identifies nine major groups who are often active in environmental negotiations: women; children and youth; Indigenous peoples; non-governmental organisations; local authorities; workers and trade unions; business and industry; the scientific and technological community; and farmers.[559] Opportunities can be enabled and implemented by state and non-state actors, with coalitions of actors working together for environmental justice against fossil fuels, to set science-based targets for business, or engaging in activism to protect indigenous land. These efforts bring together non-state actors, including scientists, businesses, and religious, labour, humanitarian, and cultural coalitions.[560–562] Both state and non-state actors can prioritise just transformations, but can also promote the special interests of people in power and fail to recognise the needs of poor and marginalised people.

The levers of governance for transformation include legal, economic, political, technological, cultural, and informational levers. Many of these levers are already deployed, but not at sufficient scale.[563,564]

There are growing calls to radically reform the UN to be able to deliver on the transformations needed. These calls include recommendations to set up an Earth governance regulatory body and to modify the UN Security Council to address peacebuilding, climate security, and health security.[565] A global solidarity pact could build on the UN Secretary General's proposal for a climate solidarity pact[32,391] and a new global deal to deliver global public goods. Such an Earth governance body and pact need to articulate and quantify the minimum rights of access to resources worldwide, and should debate and develop the safe and just ESBs that we propose. The body could, following public debate, deliberate on and globally regulate the transformations of consumption, the economic system, and technology. The adoption of the 2023 legally binding Treaty of the High Seas to protect ocean biodiversity and fight climate change shows that a multilateral system can move forwards, albeit slowly.[566]

Within countries and communities, calls for just transformations emphasise democratic and inclusive processes, including fair and transparent elections,[567] reducing the power of money in politics, and recognition and representation of minorities.[48] Transformations to enable a safe and just future include re-establishing and protecting rights to the commons, sharing resources and services, making taxation more progressive,[568] investing in benign and accessible technology, public health, and transport,[569] reducing the risks of war, and decentralising decision making.

Transformations of urban governance could make substantial contributions to reducing pressures on the Earth system, including via the building of networks of cities that share strategies and compete to be more sustainable and just.[570–573] Levers include building codes, regulation of sprawl, incentives and charges that shift transport from cars or that reduce waste, support for public parks and community gardens, subsidies for renewables and tree planting, penalties for polluters, and use of smart digital technology to manage resources such as water efficiently and equitably.[574]

Governance is one of the main mechanisms to reduce inequality,[455,575] through initiatives to reduce debt and ensure tax justice[576] and by providing public health care, energy, and food security. Limiting consumption can be incentivised through governance levers that influence personal values or behaviours, through regulation, or through development of technologies that increase efficiency or have low environmental impact. These changes in values and behaviour can improve quality of life and health (eg, improved diet, cycling, reduced workload, enjoyment of nature) and restore Earth systems.

For a **database of climate change litigation** see http://climatecasechart.com/

The legal system offers many opportunities—preventive and restorative—for transformations and can overcome barriers that include confidential state-private contracts on public goods which lead to policy freezing,[577] inappropriate property rights regimes on water,[242] insecure property rights regimes on land,[578] and the commodification and privatisation of nature. International and national or state law can prioritise public over private law to protect the global commons, and incorporate much stronger recognition of human rights,[579] eliminate monopolies over critical common resources, require reporting and monitoring, and adopt stricter regulation of utilities, building codes, emissions, pollutants, and biodiversity protection.

As already discussed, the law can also be used to implement political and value changes that redistribute wealth and resources. Although all actors can practise the precautionary principle and polluter pays principle, governments and businesses are best positioned to do so. Responsibility for harm can be addressed through liability law, extended producer responsibility, and reparations[580] in terms of compensation, mitigation, or injunction, and by making states accountable for the actions of their corporate or powerful residents within and beyond their borders. The law can be used to ban, limit, or fine polluters. Such transformations also require access to the courts and to information, recognition of standing, and the elimination of influence of powerful interests over court appointments and decisions.[120,581]

Governance transformations also need to address health and health equity by improving access to effective health programmes and by accounting for the social, cultural, economic, and political context of policies that affect health, including those related to transportation, housing and urban planning, the environment, education, agriculture, finance, taxation, and economic development.[582] Transformations of health systems can protect wellbeing and equity from the direct and indirect consequences associated with crossing ESBs and from actions taken to manage the consequences of traversing these boundaries, thereby generating synergies and co-benefits across sectors.[583–585]

## How transformations reduce pressures on the Earth system

The transformations outlined have concrete implications for how human activity asserts and resolves pressures on ESBs. The energy system and its reliance on fossil fuels is the major source of greenhouse gas emissions, changes in land use, and pollution (and associated harms).[586] Energy consumption is inequitably distributed, with millions of people lacking access to the energy that they need. Energy justice implies provision of clean electricity and other fuels to everyone to enable cooking, thermal comfort, light, economically productive use, and mobility, and also reduced reliance on fossil fuels (particularly among consumers of high amounts of energy). Even renewable energy sources rely on extractive industries[587] that are associated with effects on water resources, ecosystems, and pollution, and with injustice. Energy transitions are accelerated when energy pricing, investments, taxation, employment policies, and subsidies are restructured to reduce or eliminate fossil-fuel use, protect public health, and promote public services such as transportation, efficiency, and renewables. A just energy system is one in which job loss, workers' training, and job safety are accounted for, in which stranded resources and assets issue are dealt with equitably, and in which transformations do not lead to new lock-ins or unaffordable and unsafe energy.[536] Such a transition can be enabled by changes in values and governance, by innovative technologies, by reducing surplus consumption and accumulation and fossil-fuel subsidies, by regulating greenhouse gases, and by incentivising renewable energy and net-zero emission strategies.

Agriculture and food systems have major effects on the Earth system, especially in terms of land use and farming intensity, greenhouse gas emissions, nutrient use, soil degradation, carbon sequestration, biodiversity, water use, and pollution.[588] Greenhouse gas emissions from industrial agriculture include those from deforestation, mechanisation, livestock production, and waste.[589] Biospheric functional integrity and natural ecosystem areas are degraded by agricultural extensification, especially when large monoculture farms clear cut forests or convert grasslands. Irrigated agriculture uses the largest share of water globally. The inefficient use of nitrogen and phosphorus to increase crop yields and waste from the food system and intensive livestock production degrade water and air quality. The fundamental drivers of inefficient food systems include consumption, especially diets based on meat and dairy, food waste, unsustainable technologies such as polluting fertilisers and chemicals, trade, and speculation on agricultural land, which can involve unsustainable practices as land values increase.[590]

Proposals for more sustainable and equitable food systems focus on transformations to agro-ecological and regenerative farming, restoration of degraded ecosystems in working landscapes, reduced use of polluting chemicals, elimination of food waste, local sourcing of food, carbon sequestration in soils, production of more on existing agricultural land, and reduced methane production through changes to agricultural practices and diet.[591] Given that our water-related ESBs will substantially restrict access to surface and groundwater, there will be trade-offs in many regions. Policy options include extensive demand-side management; redesigning property rights, permits, and contracts; climate-proofing water policies and transboundary water treaties; restoring depleted aquifers through managed aquifer recharge; and conjunctive management of surface and groundwater.[592]

Transformations can be promoted through justice-focused and systemic changes in food preferences and values, the use of innovative and Indigenous technologies, government regulation and self-governance by food-system actors, the securing of property rights for small-scale farmers, food labelling (eg, to detail carbon content or that the product is forest friendly), and social support systems that provide access to food.[364,588,593–598] Returning land to nature via changed agricultural practices could require international payment for land stewardship to compensate for lost earnings.

Our translation proposals for cities include targets to influence energy use and transport options that can be met through urban design and policy.[599] Meanwhile, 30% of urban residents still need access to basic resources and services (with poor women especially vulnerable).[215] Proposals to reduce the environmental impacts of the built environment include denser urban development with accessible greenspace and community-level affordable renewable energy, electric vehicles, improved public transport, policies to support use of bicycles, building with recycled or renewable materials, introduction of shading and retrofitting to enable efficient cooling or heating, support for basic provision of drinking water and sanitation for all, public participation (eg, in decisions about the distribution of green spaces), and cultural and educational activities that encourage values of justice and sustainability.[600]

## Conclusion

A just, healthy, and safe planet is essential. Good health, including physical and mental wellbeing, is a basic human right,[601] and is at the core of the SDGs. Promoting a healthy planet for all requires an Earth-system justice approach to ensure that the critical functions of the Earth system are protected, human health and wellbeing are improved, and the minimum needs of all humans are fulfilled to enable them to prosper.

In this Commission, we identified a safe and just corridor bounded by ESBs and minimum access to resources required for two levels of justice. This framework builds on the SDGs by suggesting specific boundaries that, if adhered to, will reduce harm to people and the planet. We also investigated the Earth-system implications of providing access to required resources for wellbeing to all people. Additionally, we reviewed how ESBs can be translated for cities and business and suggest just transformations of socioeconomic systems, because growing evidence shows that it will be impossible to live within safe ESBs without addressing injustice.

International agreements already aim to address many aspects of planetary health—through, for example, the SDGs and the Climate Treaty Regime. Here we go a step further to identify safe and just boundaries and minimum access levels using the same units as guides for improving global governance of the commons.

In previous work, we identified eight safe and just ESBs for five biophysical domains.[10] At the global level, seven of these ESBs have already been crossed, and the eighth has been crossed at the local level in many parts of the world. In this Commission, we have gone a stage further than the previous global analysis to illustrate the spatial aspects of these safe and just boundaries. We show how the ESBs have been crossed in different parts of the world, leading to significant harm, especially to poor, marginalised people. However, adhering to just ESBs does not necessarily imply that they will be met through just transformations—the boundaries could be met through unjust and undemocratic processes. Therefore, we highlight the justice nuances of the boundaries and pathways to achieving them.

The safe and just corridor is a conceptual space in which everyone can have their essential needs met without compromising the stability of Earth's essential systems. The ceiling of the safe and just corridor is defined by the ESBs, and the base is defined by the minimum access needs of everyone (calculated using the same units). We used targets consistent with international assessments to define two minimum levels of access to water, food, energy, and infrastructure.[13] This thought experiment showed that, in our unequal world (as of 2018), meeting the basic needs for those who lack it would lead to further crossing of all ESBs, and, by 2050, meeting minimum access needs for everyone would result in transgressing the boundaries even further. Our analysis suggested that, in the case of climate change, even if all people in the world have minimum access to resources and no more (ie, the base of the corridor), the climate ESB would still be crossed by 2050, in the absence of technological and societal transformations. These findings do not imply that people should be denied access to basic needs to stay within safe boundaries. Rather, we argue that living within the safe and just corridor requires fundamental transformations of production and consumption systems, via more sustainable technologies, as well as redistribution of resources.

We showed how living within the safe and just corridor requires translations of the ESBs to major actors, such as cities and businesses. We identified commonly used sharing approaches in translation and assessed their alignments with an Earth-system justice framework. We discussed steps, considerations, context, and enablers of translating each ESB for cities and businesses, and showed the linkages between translated shares and impacts. We then identified four systemic transformations to enable living within the safe and just corridor: transformations in consumption, economic systems, technologies, and governance. These translations and transformations will not be easy. For example, the just ESB for climate of no more than 1°C of global warming, with millions of people without minimum access to resources and already harmed by global warming of 1·2°C, will be extremely difficult to adhere to even with rapid and deep transformations in governance, consumption, economies, and technologies. There are similar challenges with meeting the ESBs across the other domains, however, and we need to accept responsibility for significant harm already caused to other countries, communities, people, and species.

The safe and just corridor that we defined does not yet account for interactions and trade-offs between different ESBs. Despite the advance that our ESBs represent, they do not account for how staying within the ESB in one domain affects the other domains. Additionally, the just minimum access levels that we defined did not account for non-material resources and services (eg, education, health care), or for how material resources and services are linked. Such associations are particularly important for domains that are very tightly linked through anthropogenic processes, such as agricultural production, energy, nutrients, water, and biosphere natural ecosystem area. Accounting for interactions between ESBs could reshape the safe and just corridor considerably. Neither does the corridor account for the many ways that human health is affected by multiple, intersectional vulnerabilities. Future research can expand the scientific work to other domains, such as oceans and novel entities, to further develop methods to define just boundaries and transformations, develop translation processes, explore the details of trade-offs and transformations, and quantify pathways towards the safe and just corridor.

We present our results for public debate to ensure their legitimacy. What is now required is both scientific scrutiny and public debate about our numbers and framework to ensure that they are the best possible estimates. Actors worldwide need to mobilise and act on engaging with the broader systemic translations and transformations that we propose. This mobilisation is essential to protect the health and wellbeing of humans and other species, to ensure that everyone can live within the safe and just corridor, and to ensure that the responsibility for enabling this falls most heavily on those most responsible for current environmental degradation. Ultimately, the safe and just corridor provides a roadmap for a resilient and sustainable future.

**Contributors**

JG, XB, DML, JR, DQ, BS-K, JCR, LJ, JFA, LSA, DIAM, GB, SEB, DC, FD, KLE, LG, CG, NK, TML, SL, AM, NN, DOb, DOs, KP, CR, BS, JS, DvV, PHV, RW, CZ, AB, SB, WJB, HB, BC, HH, LH, MH, CYAI, ŞK, SJL, JL, CO, IMO, SP, LP, JDT, GW, CX, and XX contributed to study conceptualisation. BS-K, JCR, JFA, DIAM, DC, LG, SL, AM, CR, BS, TT, RW, PAG, MH, and IN curated the data. JG, DML, JCR, JFA, DIAM, DC, LG, TML, SL, AM, NN, KP, CR, BS, TT, PHV, RW, MH, IN, CN, and L-SU did the formal analysis. JG, DML, LJ, NN, and WJB acquired funding. JG, XB, DML, BS-K, JCR, LJ, JFA, LSA, DIAM, GB, SEB, FD, KLE, LG, CG, NK, TML, SL, AM, NN, DOb, DOs, KP, CR, BS, JS, TT, PHV, RW, CZ, EB, PAG, ŞK, CN, LS-U, JDT, WdV, NZ-C, XZ, PF, and GG contributed to investigations. JG, XB, DL, BS-K, JCR, LJ, JFA, LSA, DIAM, SEB, DC, KLE, LG, CG, TML, SL, AM, NN, CR, BS, TT, DvV, PHV, RW, CZ, AB, SB, HB, PAG, HH, MH, ŞK, JL, CN, IMO, and LP contributed to developing and implementing the methods. XB, DML, BS-K, JCR, LJ, DIAM, SEB, LG, CG, TML, NN, RW, SJL, SP, and NZ-C administered the Commission. JG, DML, DIAM, and AM contributed university resources to the project. JCR, JFA, DIAM, and PAG wrote computer code for analyses that underpin mapping. JG, XB, DML, JCR, GB, SEB, CG, TML, NN, DvV, PHV, RW, SB, WB, SJL, IMO, and SP supervised the study. JG, DML, BS-K, JCR, JFA, DIAM, LG, TML, SL, NN, CR, BS, TT, RW, CZ, EB, LP, LSU, WdV, and XZ validated modelled data. JG, XB, DML, JCR, LJ, JFA, LSA, DIAM, KLE, LG, TML, SL, CR, BS, PHV, RW, CZ, ŞK, SJL, IN, LP, and JDT created visualisations of the data. JG, XB, DML, BS-K, JCR, LJ, JFA, LSA, DIAM, GB, SEB, DC, FD, KLE, LG, CG, SH, DOs, TML, SL, AM, KP, CR, BS, TT, PHV, RW, CZ, AB, MH, ŞK, JL, CN, and JDT wrote the first draft of this Commission report, which was reviewed and edited by all authors.

**Declaration of interests**

We declare no competing interests.

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