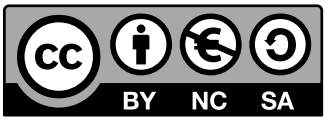
KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

PLANETARY HEALTH

AN EMERGING FIELD TO BE DEVELOPED

ADVISORY REPORT



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PLANETARY HEALTH

AN EMERGING FIELD TO BE DEVELOPED

Royal Netherlands Academy of Arts and Sciences
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FOREWORD

Planetary Health was launched as a new scientific field in 2015. It focuses on the consequences of global environmental change for the health and survival of all species living on Earth. Examples of possible effects on human health include heat stress, infectious diseases and pandemics, malnutrition, and mental health problems. Fortunately, many negative consequences can still be avoided if measures are taken in the short term.

The Academy believes that science can play an indispensable role in tackling societal challenges of this kind by establishing and analysing facts and finding solutions. This belief prompted the Academy to set up the Planetary Health Committee, charged with surveying this emerging field and drawing up a research agenda of knowledge gaps that require urgent action. For practical reasons, the committee has focused mainly on human health, which has so far been the subject of most research.

I would like to thank the committee for the enthusiasm with which it has taken up this task, its thorough analysis of the existing scientific knowledge, its longlist of outstanding research questions (compiled with the help of many national and international experts), and the research priorities identified. It is clear that we still lack knowledge about the relationship between global environmental change and human health, and about effective measures to offset the negative consequences of these environmental changes for human health. Answering the research questions will require expertise from many different disciplines. Many issues will also require a transdisciplinary approach, with non-scientific and/or societal partners contributing to the research. It is my hope and expectation that the longlist of knowledge gaps in this report will inspire researchers active in a wide range of disciplines worldwide. Crucially, researchers, civil society and local communities in low- and middle-income

countries must be involved, because these regions are most likely to face negative health consequences.

In this advisory report, the Academy also makes a number of recommendations for the successful implementation of this Planetary Health research agenda. These are to encourage the above-mentioned interdisciplinary and transdisciplinary collaboration, to integrate Planetary Health research into existing research projects and programmes, to develop new research programmes and the associated funding, and to implement and communicate knowledge. The boards of public knowledge institutions, university medical centres, research institutes and research funders, researchers themselves and health care professionals are encouraged to follow up on these recommendations.

The Academy also sees a role for itself. It has already started transferring existing knowledge about Planetary Health to a wide audience through webinars, symposia and podcasts (for an overview, see https://www.knaw.nl/planetary-health), and will continue to organise outreach activities of this kind. In addition, the Academy has a large international network that includes sister academies and their umbrella organisations. It will discuss this report with them and investigate opportunities for bringing this topic to the attention of international policymakers. Such efforts fit in seamlessly with the Academy's strategic agenda, in which one of its priorities is to offer advice based on scientific research (Science for Policy). In its international activities, climate, sustainability and health are important Science for Policy themes.

Finally, a recent and relevant initiative launched by the Academy and the Dutch Research Council (NWO) is Climate Initiative Netherlands (KIN), aimed at accelerating the transformations needed to achieve a sustainable, climate-neutral society by 2050. Health Care & Planetary Health have emerged as one of the four focus areas of this initiative (for more information, see https://english.hetkin.nl/kin-onderwerpen/). KIN is still in its start-up phase, but the research agenda proposed in this report will undoubtedly provide valuable input for its activities in this area.

Marileen Dogterom
President

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EXECUTIVE SUMMARY

Health in times of planetary changes

The conditions for life on Earth are changing profoundly. The climate crisis is causing frequent forest fires, heat waves, floods and extreme drought. Biodiversity is rapidly declining, environmental pollution has reached every corner of Earth, nitrogen is accumulating in nature, deforestation and erosion are continuing at an alarming rate, and freshwater sources are drying up.

If these global environmental changes continue unabated, billions of people worldwide may face serious health risks by the end of this century. Many millions may die every year in that event, and many more could suffer from heat stress, infectious diseases, malnutrition, flooding and mental disorders. Some human communities will find their very existence threatened as their habitat is flooded or scorched by heat or drought. According to the World Health Organization, climate change is 'the single biggest health threat facing humanity' in the 21st century.

Yet scientists are only beginning to study the impact of global environmental change on human health, and how this impact can be abated. 'Planetary Health' was launched as a new field in 2015 and has since grown rapidly. It is a broad field, going beyond the local environmental threats studied in the past and focusing on changes on a planetary scale.

This report presents the views of the Royal Netherlands Academy of Arts and Sciences (KNAW) on this emerging field. It identifies the main knowledge gaps and proposes a research agenda, assembled in consultation with a wide range of experts. Planetary Health as a scientific field is based on the understanding that all life on

Earth is interconnected, and that safeguarding the health and survival of all species is an important moral imperative. For practical reasons, however, this report focuses mainly on human health, to which most research efforts have so far been devoted.

Impact of global environmental change on human health

Scientific research shows clearly that global environmental changes are already affecting human health. More people are dying of heat stress, severe drought is causing widespread hunger, and some infectious diseases are spreading to previously uninfected areas, to mention just a few examples. While these problems are already serious ones, health impacts are expected to escalate further in the future if global environmental changes continue at their current pace.

These health impacts are the result of both direct effects, for example through heat stress or flooding, and indirect effects, for example through diminishing food yields and the spread of infectious diseases, and through migration and conflict. Such indirect effects probably affect more people than direct effects, but are much more difficult to investigate because of longer causal chains. Nevertheless, a better understanding of these indirect effects, particularly those through nutrition and infection, is essential for the development of effective countermeasures.

Not all countries will be equally affected. High-income countries, like the Netherlands, will probably be able to manage the health effects of global environmental change in the short and medium term, although they will need to develop and implement adaptation plans, for instance to reduce the impact of heat waves or floods. Much greater health risks threaten the Global South, which is more vulnerable to these environmental changes and whose populations often lack the resources necessary for taking countermeasures. Because the prosperity of richer countries is based on their larger ecological footprint over many centuries, however, they are largely responsible for environmental changes elsewhere in the world and their health consequences.

Our knowledge of the health effects of global environmental changes varies. We know more about the health effects of climate change and the global pollution of air, water and soil than about the health effects of biodiversity loss and disruption of the nitrogen cycle. In the case of biodiversity loss, for example, empirical evidence is particularly scarce. Yet it is clear that human health depends in part on nature's 'ecosystem services', including the purification of water and air, support for food production and management of infectious diseases. These will come under increasing pressure when biodiversity declines.

Abating the causes of global environmental changes by effective 'mitigation' policies is crucial to preventing their health impacts. Because these changes are ultimately driven by rising human population numbers and increasing production and consumption per capita, it is worrying that both are expected to keep growing in the short and medium term. It is an open question whether technological adaptations, such as the transition to renewable energy, can turn the tide or whether more drastic changes are necessary, such as a contraction of material production and consumption ('degrowth').

In either case, transformative changes will be necessary to the energy supply, transportation, industry, food production and other core sectors. For some, i.e., the transformation of the energy system, technological solutions are in sight, raising hopes that we can halt some of the global environmental changes in time. Yet policymakers, private companies, public institutions and individual citizens will need to fundamentally change their policies and behaviours to achieve these transformative changes. They will need to overcome ingrained habits, vested interests and other major barriers.

Health care also has a substantial ecological footprint, and contributes significantly to greenhouse gas emissions, pollution and other global environmental changes. Like other sectors, it will have to switch to more sustainable ways of delivering its services. In addition, health care has an important role to play in adaptation, for example when it comes to combating infectious diseases induced by climate change.

The need for Planetary Health research

There are many knowledge gaps in the field of Planetary Health. A review of the literature and a subsequent consultation with experts have resulted in a longlist of more than one hundred specific knowledge gaps. Evidence of the human health effects of global environmental change is incomplete, pathways are insufficiently understood, the effectiveness of mitigation and adaptation policies has not yet been firmly established, and it is currently unclear how timely policy and behaviour change can be realised.

The longlist is divided into four research areas: (A) effects of global environmental changes on human health; (B) developing effective mitigation and adaptation measures; (C) promoting the implementation of these measures; and (D) data and methods of Planetary Health research. There are important scientific challenges in each of these areas, which in most cases can only be studied through interdisciplinary research and by taking a 'transdisciplinary' approach that involves non-scientific partners. Many issues will also require collaboration with partners in low- and middle-income countries. Some examples of open research questions are given in the box below.

EXAMPLES OF OPEN RESEARCH QUESTIONS IN PLANETARY HEALTH

- What is the effect of combined global environmental changes (e.g., climate change, deforestation and biodiversity loss) on the spread of infectious diseases?
- What is the environmental impact of medicines, single-use gloves and other materials and equipment used in health care, and which should be prioritised for replacement?
- How does energy poverty change food choices? What incentive schemes for switching to renewable energy have the largest health co-benefits and avoid a widening of health inequalities?
- What is an optimal diet for Western Europeans and other populations around the world, taking into account climate change, biodiversity protection, health effects and affordability?
- How can preventive measures, for example proper ventilation, social distancing and face masks, make societies more resilient to pandemics should they occur more frequently as a result of global environmental change?
- How can societies adapt to more frequent extreme weather events, sea level rise and other climate change-related risks in order to avoid their health consequences?
- How can health care professionals help their patients adopt behaviour beneficial to their health and at the same time minimise greenhouse gas emissions and other environmental impacts?
- How can international environmental treaties help advance national health policies so that environmental protection goes hand-in-hand with health improvement?

Experts also selected the most urgent research questions from the longlist, based on relevance to policy and the speed with which results can be achieved. Four priority areas emerged: (1) integral analyses of the effects of global environmental change on human health; (2) research guiding and supporting the transformative changes necessary to avert global environmental change; (3) research on methods for individual and collective behaviour change and governance in relation to global environmental change; (4) research guiding and supporting mitigation and adaptation strategies for the health care sector.

Conclusions and recommendations

If climate change, biodiversity loss and other global environmental changes continue at their current pace, the foundations for human health will be seriously jeopardised. This means, first of all, that it is essential to reverse these trends. The Academy sees an important role for scientific organisations in communicating the risks of global environmental change and in advocating evidence-based solutions. The Academy also advises health care leaders to increase their involvement in sustainability debates and to help achieve the urgent societal changes necessary to avoid the health consequences of global environmental change.

Science has a key role to play in averting these health risks, not only by actively sharing available knowledge but also by filling important gaps in the knowledge base. This implies that the emerging field of Planetary Health needs to be promoted and developed. Although human health is by no means the only factor affected by climate change, biodiversity loss and other global environmental changes, it is certainly important enough to receive separate attention in research. Not only will better scientific understanding enable more effective policies, but greater awareness of the health risks of global environmental change may also help to speed up the necessary changes in the behaviour of policymakers, private companies, public institutions and individual citizens.

This report proposes an ambitious research agenda for Planetary Health. Researchers from many disciplines may find starting points here for involving themselves in this field. Adding a health dimension to studies of global environmental change, and adding a global environmental dimension to medical and health research wherever appropriate, would already be a solid first step. The Academy also recommends the creation of an interinstitutional and interdisciplinary network for Planetary Health research in the Netherlands, linked to similar international initiatives. While it is true that many universities and research institutes can contribute to this development by clearing more space for Planetary Health issues in their research portfolios, the Academy recommends in particular that the Dutch university medical centres step up their efforts in this emerging field.

Getting started in Planetary Health research will not always require new funding: existing programmes in the Netherlands already provide a few opportunities for obtaining research grants. These are inadequate, however, and the Academy therefore calls on research funders in the Netherlands to explore options for incentivising research in the face of the increasing threats to human health posed by global environmental change. For example, the four priority research areas in Planetary Health mentioned above lack proper funding options, despite being highly relevant to policy. For example, it would be very useful to create more funding opportunities for research into health care sustainability issues with a view to speeding up the transition of the health care system. If funding were conditional on participation in an interdisciplinary and interinstitutional network, this would also catalyse the formation of a Planetary Health community in the Netherlands.

Finally, this report shows that the research agenda for Planetary Health far exceeds the scope of the Dutch research community. International cooperation will therefore be essential. Such cooperation can be promoted by bringing together national and international actors in this field, including national and international academies and research funders, to discuss the international coordination of research agendas and research funding in the field of Planetary Health.

SAMENVATTING

Gezondheid in tijden van mondiale milieuveranderingen

De omstandigheden voor het leven op aarde zijn ingrijpend aan het veranderen. De klimaatcrisis veroorzaakt regelmatig bosbranden, hittegolven, overstromingen en extreme droogte. De biodiversiteit neemt snel af, de milieuvervuiling is tot in alle uithoeken van de aarde doorgedrongen, stikstof hoopt zich op in de natuur, ontbossing en bodemerosie gaan in een alarmerend tempo door en drinkwaterbronnen drogen op.

Als deze wereldwijde milieuveranderingen onverminderd doorgaan, kunnen eind deze eeuw wereldwijd miljarden mensen te maken krijgen met ernstige gezondheidsrisico's. Jaarlijks zouden daar miljoenen mensen aan kunnen overlijden, en nog veel meer mensen zullen te kampen krijgen met hittestress, infectieziekten, ondervoeding, overstromingen en psychische problemen. Sommige gemeenschappen zullen worden bedreigd in hun voortbestaan omdat hun omgeving overstroomt of onleefbaar wordt door hitte of droogte. Volgens de Wereldgezondheidsorganisatie is klimaatverandering zelfs 'de grootste bedreiging voor de volksgezondheid' in de eenentwintigste eeuw.

Desondanks staat het onderzoek naar de gevolgen van wereldwijde milieuveranderingen voor de menselijke gezondheid, en hoe die kunnen worden beperkt, nog in de kinderschoenen. *Planetary health* is in 2015 als nieuw vakgebied geïntroduceerd en sindsdien snel gegroeid. Het is een breed vakgebied, dat verder kijkt dan de lokale milieubedreigingen die tot nu toe zijn onderzocht, en richt zich op veranderingen op mondiale schaal.

In dit rapport wordt de visie van de Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) op dit nieuwe vakgebied gepresenteerd. Het inventariseert

de belangrijkste kennislacunes en presenteert een onderzoeksagenda die in overleg met deskundigen uit allerlei disciplines tot stand is gekomen. *Planetary health* als wetenschapsterrein heeft als uitgangspunt dat al het leven op aarde onderling verbonden is, en dat het onze morele plicht is om te zorgen voor de gezondheid en het voortbestaan van alle soorten. Om praktische redenen richt deze verkenning zich echter voornamelijk op de gezondheid van de mens, waarnaar tot dusver het meeste onderzoek is gedaan.

Gevolgen van wereldwijde milieuveranderingen voor de volksgezondheid

Uit wetenschappelijk onderzoek blijkt zonder meer dat wereldwijde milieuveranderingen ook nu al invloed hebben op de volksgezondheid. Er overlijden meer mensen aan hittestress; ernstige droogte veroorzaakt op grote schaal honger; en sommige infectieziekten verspreiden zich naar gebieden waar ze eerder niet voorkwamen – om maar een paar voorbeelden te noemen. Hoewel dit dus nu al ernstige problemen oplevert, zullen de gezondheidseffecten in de toekomst naar verwachting nog veel groter worden als de wereldwijde milieuveranderingen in het huidige tempo doorgaan.

Hierbij kan het gaan om directe gezondheidseffecten, bijvoorbeeld als gevolg van hittestress of overstromingen, maar ook om indirecte effecten, bijvoorbeeld door lagere voedselopbrengsten, de verspreiding van infectieziekten, of migratie en conflicten. Door dergelijke indirecte effecten worden waarschijnlijk meer mensen getroffen dan door directe effecten, maar de indirecte zijn veel lastiger te onderzoeken vanwege de langere causale ketens. Desondanks is beter inzicht in deze indirecte effecten essentieel om tot effectieve maatregelen te komen, met name als het gaat om voeding en infectieziekten.

Niet alle landen zullen even zwaar worden getroffen. Rijke landen, zoals Nederland, zullen de gezondheidseffecten van wereldwijde milieuveranderingen op de korte en middellange termijn waarschijnlijk wel kunnen opvangen, mits ze de nodige aanpassingsmaatregelen treffen, bijvoorbeeld om de gevolgen van hittegolven of overstromingen te beperken. De gezondheidsrisico's zijn veel groter in het mondiale Zuiden, dat kwetsbaarder is voor deze milieuveranderingen en vaak ook niet over de nodige (financiële) middelen beschikt om maatregelen te nemen. En omdat de welvaart van de rijkere landen samenhangt met een al eeuwenlang grotere ecologische voetafdruk, zijn zij grotendeels verantwoordelijk voor milieuveranderingen elders in de wereld en de gevolgen daarvan voor de gezondheid.

Er zijn grote verschillen in kennis over de gezondheidseffecten van de diverse mondiale milieuveranderingen. We weten bijvoorbeeld meer over de gezondheidseffecten van klimaatverandering en wereldwijde lucht-, water- en bodemverontreiniging dan over de gezondheidseffecten van biodiversiteitsverlies en verstoring van de stikstofkringloop. Vooral als het gaat om het verlies van biodiversiteit is er maar weinig empirisch bewijs voor de gezondheidseffecten ervan. Toch staat vast dat de gezondheid van de mens mede afhankelijk is van de 'ecosysteemdiensten' van de natuur, zoals het zuiveren van water en lucht, het mogelijk maken van voedselproductie en het beheersen van infectieziekten. Als de biodiversiteit afneemt, komen deze steeds meer onder druk te staan en ontstaan ook grote gezondheidsrisico's voor mensen.

Om gevolgen voor de volksgezondheid te voorkomen is het essentieel om de oorzaken van wereldwijde milieuveranderingen aan te pakken met een effectief 'mitigatiebeleid'. Omdat deze milieuveranderingen uiteindelijk het gevolg zijn van de groeiende wereldbevolking en de toenemende productie en consumptie per persoon, is het zorgwekkend dat deze beide ontwikkelingen op de korte en middellange termijn naar verwachting zullen doorzetten. Het is de vraag of technologische aanpassingen, zoals de transitie naar duurzame energie, het tij nog kunnen keren, of dat er meer drastische maatregelen nodig zijn, zoals inkrimping van de materiële productie en consumptie ('degrowth').

In beide gevallen zullen transformatieve veranderingen nodig zijn in de energievoorziening, het vervoer, de industrie, de voedselproductie en andere essentiële sectoren. Voor sommige daarvan, met name de verduurzaming van het energiesysteem, zijn er technologische oplossingen in zicht, waardoor bepaalde wereldwijde milieuveranderingen hopelijk nog tijdig tot staan kunnen worden gebracht. Beleidsmakers, bedrijven, overheidsinstellingen en individuele burgers zullen echter hun beleid en hun gedrag grondig moeten aanpassen om deze transformaties tot stand te brengen. Daarvoor zullen vaste gewoonten, gevestigde belangen en andere grote belemmeringen moeten worden doorbroken.

De gezondheidszorg heeft ook zelf een aanzienlijke ecologische voetafdruk en draagt flink bij aan de uitstoot van broeikasgassen, verontreiniging en andere wereldwijde milieuproblemen. Net als andere sectoren zal de zorg daarom duurzamer moeten worden. Daarnaast speelt de gezondheidszorg een belangrijke rol in de adaptatie, bijvoorbeeld bij de bestrijding van infectieziekten die samenhangen met klimaatverandering.

De noodzaak van *planetary health* onderzoek

Er ontbreekt nog veel kennis op het gebied van *planetary health*. Literatuuronderzoek en overleg met deskundigen heeft geleid tot een longlist van meer dan honderd concrete kennishiaten. Wetenschappelijk bewijs voor de gezondheidseffecten van wereldwijde milieuveranderingen is onvolledig, er is onvoldoende inzicht in de mechanismen die hierbij een rol spelen, de effectiviteit van mitigatie- en adaptatiebeleid staat nog niet echt vast, en het is nog onduidelijk hoe beleids- en gedragsverandering tijdig kan worden gerealiseerd.

De longlist is onderverdeeld in vier onderzoeksgebieden: (A) effecten van wereldwijde milieuveranderingen op de volksgezondheid; (B) ontwikkeling van doeltreffende mitigatie- en adaptatiemaatregelen; (C) bevordering van de uitvoering van deze maatregelen; en (D) gegevens van en methoden voor *planetary health* onderzoek. Op elk van deze gebieden liggen grote wetenschappelijke uitdagingen, die in de meeste gevallen alleen kunnen worden opgelost door middel van interdisciplinair onderzoek en een 'transdisciplinaire' aanpak waarbij ook niet-wetenschappelijke partners betrokken zijn. Voor veel problemen zal ook samenwerking met partners in lage- en middeninkomenslanden nodig zijn. In het onderstaande kader staan enkele voorbeelden van open onderzoeksvragen.

VOORBEELDEN VAN OPEN ONDERZOEKSVRAGEN INZAKE PLANETARY HEALTH

- Welk effect hebben combinaties van wereldwijde milieuveranderingen (bijv. klimaatverandering, ontbossing en verlies van biodiversiteit) op de verspreiding van infectieziekten?
- Wat is de milieuschade van geneesmiddelen, wegwerphandschoenen en andere in de zorg gebruikte materialen en apparatuur, en welke moeten als eerste worden vervangen?
- Welke invloed heeft energiearmoede op de voedselkeuze? Welke stimuleringsregelingen voor de overschakeling op duurzame energie hebben de grootste bijkomende gezondheidsvoordelen en voorkomen dat gezondheidsverschillen groter worden?
- Wat is een optimaal voedingspatroon voor West-Europeanen en andere populaties, rekening houdend met klimaatverandering, bescherming van de biodiversiteit, gezondheidseffecten en betaalbaarheid?
- Hoe kunnen preventieve maatregelen zoals ventilatie, *social distancing* en mondkapjes de samenleving beter beschermen tegen pandemieën, wanneer deze door wereldwijde milieuveranderingen vaker zouden voorkomen?
- Hoe kan de samenleving zich aanpassen aan het vaker optreden van extreem weer, de stijging van de zeespiegel en andere klimaatgerelateerde risico's, om de gevolgen daarvan voor de gezondheid te voorkomen?

- Hoe kunnen zorgprofessionals hun patiënten helpen om gezond te leven, en tegelijkertijd stimuleren de uitstoot van broeikasgassen en andere milieueffecten zo veel mogelijk te beperken?
- Hoe kunnen internationale milieuverdragen een positieve rol spelen in nationaal gezondheidsbeleid, zodat milieubescherming hand in hand gaat met gezondheidswinst?

Deskundigen hebben ook de meest urgente onderzoeksvragen uit de longlist geselecteerd, op basis van hun beleidsrelevantie en de snelheid waarmee resultaat kan worden geboekt. Hieruit zijn vier onderzoeksprioriteiten naar voren gekomen: (1) integrale analyses van de effecten van wereldwijde milieuveranderingen op de volksgezondheid; (2) onderzoek om richting en ondersteuning te geven aan de transformaties die wereldwijde milieuveranderingen moeten afwenden; (3) onderzoek naar methoden voor individuele en collectieve gedragsverandering en governance in relatie tot wereldwijde milieuveranderingen; (4) onderzoek om richting en ondersteuning te geven aan mitigatie- en adaptatiestrategieën voor de gezondheidszorg.

Conclusies en aanbevelingen

Als de klimaatverandering, het verlies van biodiversiteit en andere wereldwijde milieuveranderingen in hetzelfde tempo doorgaan, komen de pijlers onder de menselijke gezondheid ernstig in gevaar. Dit betekent allereerst dat het essentieel is om deze trends te keren. De KNAW ziet een belangrijke rol weggelegd voor wetenschappelijke organisaties om de risico's van wereldwijde milieuveranderingen onder de aandacht te brengen en te pleiten voor evidence-based oplossingen. Verder is het advies van de KNAW aan leiders in de gezondheidszorg om meer betrokken te zijn bij het duurzaamheidsdebat, en mee te werken aan de dringend noodzakelijke maatschappelijke veranderingen om de gevolgen van wereldwijde milieuveranderingen voor de gezondheid af te wenden.

De wetenschap speelt een sleutelrol bij het afwenden van deze gezondheidsrisico's, niet alleen door de beschikbare kennis actief te delen, maar ook door belangrijke kennishiaten op te vullen. Dit betekent dat het nieuwe vakgebied *planetary health* moet worden gestimuleerd en verder worden ontwikkeld. Weliswaar is onze gezondheid lang niet het enige dat schade ondervindt van klimaatverandering, verlies van biodiversiteit en andere wereldwijde milieuveranderingen, maar gezondheid is zonder meer belangrijk genoeg als afzonderlijk aandachtsgebied in het onderzoek. Meer wetenschappelijk inzicht zal beter beleid mogelijk maken, maar daarnaast kan bewustwording van de gezondheidsrisico's van wereldwijde milieuveranderingen ook helpen om de noodzakelijke gedragsveranderingen bij beleidsmakers, bedrijven, overheidsinstellingen en individuele burgers te versnellen.

In dit rapport wordt een ambitieuze onderzoeksagenda voor *planetary health* gepresenteerd. Wetenschappers uit allerlei disciplines kunnen hierin aanknopingspunten vinden om aan de slag te gaan. Een goede eerste stap zou al zijn om – waar mogelijk en zinvol – een gezondheidsdimensie op te nemen in onderzoek naar wereldwijde milieuveranderingen, en een wereldwijde milieudimensie op te nemen in medisch en gezondheidsonderzoek. De KNAW adviseert ook om in Nederland een interinstitutioneel en interdisciplinair onderzoeksnetwerk rond *planetary health* op te zetten, gekoppeld aan vergelijkbare internationale initiatieven. Veel universiteiten en onderzoeksinstituten kunnen bijdragen aan deze ontwikkeling door in hun onderzoeksportefeuille meer plaats in te ruimen voor *planetary health*, maar de KNAW adviseert met name de universitaire medische centra om hun inzet op dit nieuwe vakgebied te intensiveren.

Om onderzoek naar *planetary health* van de grond te krijgen, is niet altijd nieuwe financiering nodig: bestaande programma's in Nederland bieden al mogelijkheden voor onderzoekssubsidies. Deze zijn echter onvoldoende, en de KNAW roept onderzoeksfinanciers in Nederland dan ook op om te verkennen welke mogelijkheden er zijn voor het stimuleren van onderzoek in verband met de toenemende gezondheidsrisico's als gevolg van wereldwijde milieuveranderingen. Immers, voor de vier bovengenoemde onderzoeksprioriteiten op het gebied van *planetary health* ontbreken goede financieringsmogelijkheden, ondanks hun enorme beleidsrelevantie. Zo zou het zeer zinvol zijn om meer financieringsmogelijkheden te creëren voor onderzoek naar duurzaamheidsvraagstukken in de gezondheidszorg, om de transitie van de zorg te versnellen. Als financiering afhankelijk wordt gesteld van deelname aan een interdisciplinair en interinstitutioneel netwerk, zou dit ook een impuls geven aan de totstandkoming van een platform op het gebied van *planetary health* in Nederland.

Tot slot blijkt uit deze verkenning dat de onderzoeksagenda voor *planetary health* de capaciteit van de Nederlandse wetenschap ver te boven gaat. Internationale samenwerking zal dan ook essentieel zijn. Deze kan worden bevorderd door nationale en internationale actoren op dit gebied (waaronder nationale en internationale academies en onderzoeksfinanciers) bijeen te brengen voor overleg over de internationale afstemming van onderzoeksagenda's en de financiering van onderzoek op het gebied van *planetary health*.

1. INTRODUCTION

1.1 Global environmental change and human health

It is now well established that the global environment has changed profoundly as a result of human activity and population growth. These changes have not only affected Earth's atmosphere, for example due to greenhouse gas emissions, but also its soil, its waters and its ecosystems (McNeill, 2000; IPCC, 2021).

While these changes started centuries, and sometimes even millennia, ago, they have accelerated since 1945, to the extent that scientists see the start of a new geological epoch (the Anthropocene), in which human action has become the most important factor governing Earth's natural processes. The root cause of this 'Great Acceleration' is escalating economic expansion combined with continuing human population growth (McNeill & Engelke, 2016).

Although economic growth has brought great benefits to human health and well-being, there are rising concerns that the accelerated degradation of the environment will have starkly negative effects on human health. Climate change, biodiversity loss, global pollution of air, waters and soils, and other global environmental changes are likely to affect human health sooner or later, either directly or indirectly, and in some cases they are already causing human suffering on a major scale (Myers & Frumkin, 2020; Haines & Frumkin, 2021).

The COVID-19 pandemic was a powerful reminder of the many potential links between human health and global environmental changes.[1] This heightened awareness led the Royal Netherlands Academy of Arts and Sciences (KNAW) to establish a Planetary Health Committee whose remit is to (1) survey the state of scientific knowledge in this field and list the main knowledge gaps, and (2) prepare an agenda for knowledge development in this field in the Netherlands.[2] This report presents the Committee's results and the Academy's main conclusions and recommendations.

1.2 The emerging field of Planetary Health

The term Planetary Health was introduced in the 2010s in an initiative launched by the Rockefeller Foundation and *The Lancet* (Horton et al., 2014; Whitmee et al., 2015). Since then, it has rapidly become popular, as illustrated by the founding of a dedicated scientific journal,[3] interdisciplinary university centres and professorships,[4] and an international network to support advocacy and action in the field of Planetary Health.[5] Two textbooks have also recently been published (Myers & Frumkin, 2020; Haines & Frumkin, 2021).

Planetary Health is a very broad field. In the 2015 *Lancet* publication, it was defined as 'the achievement of the highest attainable standard of health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity *and* the Earth's natural systems that define the safe environmental limits within which humanity can flourish. Put simply, planetary health is the health of human civilisation and the state of the natural systems on which it depends' (Whitmee et al., 2015). Since then, various other definitions have been proposed, such as 'Planetary Health is a solutions-oriented, transdisciplinary field and social movement focused on analyzing and addressing the impacts of human disruptions to Earth's natural systems on human health and all life on Earth'.[6]

1 Although this pandemic is not directly linked to biodiversity loss, it illustrates that the same unsustainable exploitation of the environment driving biodiversity loss (e.g., agricultural expansion and intensification, deforestation and wildlife trade and consumption) also increases the risk of pandemics among humans (IPBES, 2020).
2 The Academy's resolution inaugurating the Committee can be found in Appendix 1.
3 https://www.thelancet.com/journals/lanplh/home
4 'World's first professor of planetary health appointed'. https://www.sydney.edu.au/news-opinion/news/2016/10/31/university-of-sydney-appoints-worlds-first-professor-of-planetar.html (Consulted 31 May 2022). Other examples include the appointment, as of 1 September 2022, of Pim Martens as Professor of Planetary Health at Maastricht University.
5 https://www.planetaryhealthalliance.org/planetary-health
6 https://www.planetaryhealthalliance.org/planetary-health

Important elements in these and other definitions[7] are: (1) Planetary Health deals with man-made (anthropogenic) changes to the global environment, such as climate change, biodiversity loss, global pollution and deforestation; (2) Planetary Health deals with the impact of these global environmental changes on the health of humans as well as on other species; (3) Planetary Health is not only a field of research, but also a field of practice and policy, perhaps even a 'movement'; (4) Planetary Health is by necessity interdisciplinary, and should also be transdisciplinary, in the sense that research should often be conducted in collaboration with non-scientific and/or societal partners.

While such broad definitions are undoubtedly useful, it was necessary for this report to focus on a subset of all the issues that could potentially fall under the Planetary Health heading. Both the review of available evidence and the survey of knowledge gaps were therefore limited to the links between global environmental change and *human health.*[8] This demarcation does not signal that the Academy disagrees with the moral values that underpin a broader scope that includes other species. Practical reasons dictated our narrowing the scope of this report, as the Committee's task would have otherwise become unmanageable, but this decision is entirely in line with how Planetary Health has actually developed since being introduced as a new field of study.[9] This report in fact deals primarily with Planetary Health *research*, although a few recommendations will also be made regarding science communication and Planetary Health education.

Figure 1 illustrates what this implies for the aspects of Planetary Health to be covered in this report. 'Human health' is conceived of as capturing not only the presence or absence of specific diseases, but also such aspects as mental well-being, hunger, violence and health equity. Important pathways between global environmental change and human health, such as nutrition, infection and migration, will be included as well. Furthermore, health-related drivers of global environmental change (particularly the effects of health care itself on the global environment) will

7 It is important to note that the term 'planetary health' is sometimes used more loosely than in the definitions cited above to refer to the idea that, metaphorically speaking, planet Earth may be healthy or sick, and that, ultimately, human health depends on 'the health of the planet'. While this may be useful for communication purposes, this report will employ the term in the more specific sense explained in this paragraph.

8 In the remainder of this report, the term 'health' therefore always refers to 'human health', unless specified otherwise.

9 For example, both Planetary Health textbooks, while subscribing to the moral values underpinning a broader scope, focus largely on risks to human health. This is illustrated by their subtitles (e.g., *Protecting nature to protect ourselves*, Myers & Frumkin 2020) and by the inclusion of '[human] health' in many chapter headings (Myers & Frumkin, 2020; Haines & Frumkin, 2021). Planetary Health's focus on human health has also been identified as one of the main differences between it and One Health or EcoHealth (Lerner & Berg, 2017).

be covered, as well as the health aspects of policies intended to mitigate or adapt to global environmental change. The physical, chemical, biological and other aspects of global environmental change that have no clear link to human health will not be covered, and the same applies to the technological aspects of solutions addressing global environmental change. As will be argued more extensively later, all this indeed requires interdisciplinary, and often transdisciplinary, work.[10]

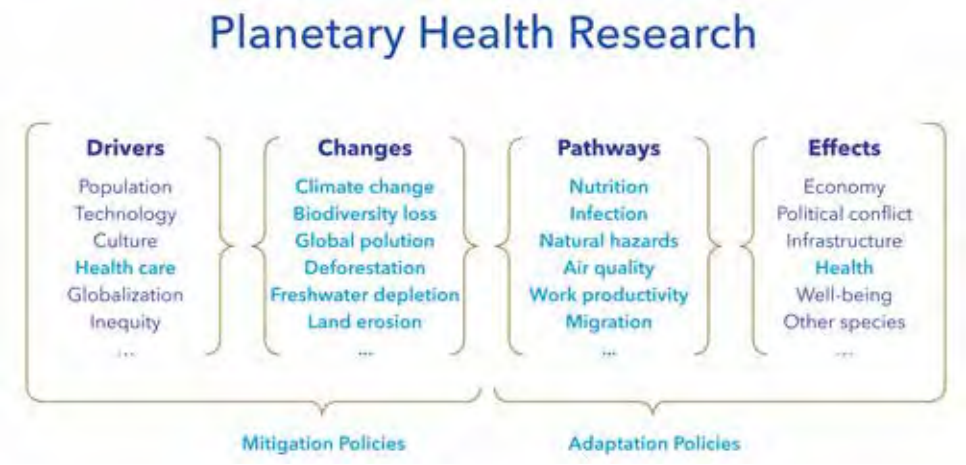

Figure 1. Planetary Health as covered in this report. The texts in light blue are the aspects of Planetary Health covered in this report: health-related drivers of global environmental change (particularly the effects of health care itself on the global environment), health aspects of policies intended to mitigate or adapt to global environmental change, pathways and human health effects.

Although the term and the field of Planetary Health are new, the ideas behind it are not. It is merely the latest among a number of new terms that all express a heightened awareness of the importance of Earth's physical and natural systems for human health. While the term has gained traction within the wider field of public health (and elsewhere to some extent[11]), other terms have become popular in neighbouring fields, with slightly different but overlapping meanings.

10 The Academy uses the term 'interdisciplinarity' in the sense of 'the combination and integration of research methods, theories, epistemological schools, procedures and/or data from two or more scientific disciplines' and 'transdisciplinary' research is research conducted 'in collaboration with non-scientific and/or societal partners, in order to use the knowledge, skills and experience of parties of these other parties' (AWTI, 2022).

11 The term 'planetary health' was also used in *The Economist's* special *Planetary Health* edition (2014).

One important example is One Health, which has been defined as 'a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environment'.[12] Although One Health research is usually focused on infectious diseases and issues such as food safety, controlling the transmission of infections from animals to humans (zoonosis), and combatting antibiotic resistance (WHO, 2017b; RIVM, 2020), One Health researchers are increasingly also interested in climate change, biodiversity loss and other global environmental changes.[13] Another example is EcoHealth, which deals with 'how changes in the earth's ecosystems affect human health'. EcoHealth brings together physicians, ecologists, life scientists, social scientists, agricultural scientists, landscape and urban planners, and so on.[14] [15]

Although Planetary Health is a relatively new field, there is already a substantial body of knowledge, derived in part from efforts in older and/or neighbouring fields of research. The overall conclusion is that in the medium to long term, global environmental changes such as climate change, biodiversity loss, global pollution and deforestation pose very serious ('potentially disastrous') risks to human health worldwide. Urgent action is required to counter these changes by deep-cutting 'mitigation' strategies (i.e., strategies that stop or reverse global environmental change) while simultaneously preparing for the worst with effective 'adaptation' strategies.

This implies that scientists' responsibility does not end with their conducting the best possible research into Planetary Health. When global environmental changes —if not averted—do indeed expose humanity to great risks, scientists should also take responsibility for communicating those risks, not only to policymakers but also to the general public and in educational settings. This advisory report therefore also includes recommendations for how scientists, including national academies of science, should deal with this wider responsibility.[16]

12 https://www.cdc.gov/onehealth/index.html

13 As shown by a recent series in *The Lancet* (Lancet 2023). [Editorial]. One Health: a call for ecological equity. The Lancet, 2023;401(10372):169.

14 'Health Ecology'. https://en.wikipedia.org/wiki/EcoHealth (Consulted 31 May 2022). 'EcoHealth Alliance'. https://www.ecohealthalliance.org/about (Consulted 31 May 2022)

15 See Appendix 5 for a more detailed description of Planetary Health and related fields.

16 Please note that in this report we use the term 'scientist' in a generic sense, i.e., not limited to those specialised in the natural sciences but including practitioners of the social sciences and the humanities.

1.3 Outline of the report

Chapter 2 reviews the state of scientific knowledge in the field of Planetary Health. As the review shows, the available evidence of the effects of global environmental change on human health is already substantial, but it also has many blank spots, for example regarding how these effects can be averted. Chapter 3 presents an in-depth analysis of knowledge gaps and research priorities. Knowledge gaps were identified using published knowledge agendas and expert consultation and compiled into a 'longlist'. This longlist was then resubmitted to experts to elicit priorities for research and discover barriers to and opportunities for conducting this type of research. The complete longlist is published as a separate downloadable file, making it easy for researchers and policymakers to use. It can be found in Appendix 2. Finally, Chapter 4 presents the Academy's main conclusions and recommendations, not only with regard to the knowledge gaps and research priorities but also addressing how conditions for Planetary Health research in the N etherlands can be optimised. Although Chapters 2 and 3 form the scientific underpinning of Chapter 4, the latter can be read independently, so that readers who are short on time can jump immediately to the main conclusions and recommendations. The report's intended audience consists of scientists and policymakers with a potential interest in Planetary Health, both in the Netherlands and elsewhere.

Additional information can be found in various appendices. The literature review was prepared in the second half of 2021, implying that it basically covers the state of knowledge up to and including 2020. The analysis of knowledge gaps, which included extensive expert consultation, was carried out in the first half of 2022. This was followed in the second half of 2022 by a further exploration of how the Committee's recommendations could best be implemented.

2. GLOBAL ENVIRONMENTAL CHANGE AND HUMAN HEALTH: THE EVIDENCE

This chapter summarises what we know about the interlinkages between global environmental change and human health. The evidence will be presented in three parts addressing the following questions: (2.1) Which global environmental changes are likely to affect human health, and what are the pathways linking these changes to human health? (2.2) What are the drivers of these global environmental changes, and what is the role of health (and health care) in driving these changes? (2.3) How can these global environmental changes and their effects be averted, and what is the role of health (and health care) in mitigation and adaptation policies? The final paragraph (2.4) presents the Committee's general conclusions.[17]

2.1 Impact of global environmental change on human health

General overview

Changes in the global environment that are likely to have an impact on human health include climate change, biodiversity loss, global pollution of air, water and soils, altered biogeochemical cycles of nitrogen and phosphorus, land use and land cover change, and depletion of freshwater and arable land.[18] Although some of the

17 See Appendix 5 for the full version of the literature review, including all references.

18 These six changes have been distilled from several listings published in the literature: Whitmee et al., 2015; Rockström et al., 2009 and Myers & Frumkin, 2021. Further details regarding what these changes entail will be given in later parts of this chapter.

effects are expected to be positive (e.g., global warming will decrease cold-related mortality), the net effect on human health worldwide will likely be acutely negative. Some effects are already becoming manifest (e.g., a rise in heat-related mortality), but the overall conclusion based on the literature is that far more serious effects can be expected in the future if no countermeasures are taken.

Another general observation is that evidence of the health effects of different types of global environmental change varies considerably. Climate change and global pollution are relatively well covered in the scientific literature, partly because their health effects can already be observed, whereas the evidence base for other environmental changes is much thinner. This should, however, not mislead us into thinking that these other changes are less dangerous. It may be difficult to quantify the future health effects of accelerating freshwater depletion, but there is no doubt that human life is utterly dependent on freshwater.

Inequalities and human health

The burden of ill health caused by global environmental change will not be shared equally around the world. Most of the effects on human health are expected to occur in the Global South, and not in high-income countries such as the Netherlands, which are relatively well protected by their economic, technological and government resources. The Netherlands also lies in a temperate climate zone, where the balance between the positive and negative health effects of global warming will be more favourable than in other world regions, as illustrated by studies on the effects of changes in ambient temperature on mortality (Gasparrini et al., 2017; Burkart et al., 2022).

It would be unethical for high-income countries to ignore the health effects elsewhere, however, because their large ecological footprints, both now and in the past, are largely responsible for global environmental change (and thus for its health effects, regardless of where) (Costello et al., 2009; Chancel et al., 2023). It would also be unwise for wealthy countries to rely on their relative protection, because the consequences of global environmental change may well destabilise international economic and political relationships, undercutting their current advantage.[19]

Global environmental change is not only expected to exacerbate inequalities in health between countries, but also to widen inequalities in health *within* countries. Climate change, for example, will hit disadvantaged groups more severely because they are more exposed to its hazards (e.g., more work in outdoor occupations), are more susceptible to its effects (e.g., less access to air conditioning), and less able to cope and recover (e.g., less access to health care) (Islam & Winkel, 2017).

19 See, e.g., Sending et al., 2019.

These inequalities are even more problematic when we consider that high-income individuals have always had much larger ecological footprints than low- income individuals. For example, over the 1990 – 2015 period, the richest 10% of the world's population were responsible for 52% of the cumulative carbon dioxide emissions, whereas the poorest 50% were responsible for just 7% of cumulative emissions (Kartha et al., 2020).

Climate change and human health

Fossil fuel emissions and the accumulation of greenhouse gases in the atmosphere are resulting in changes in Earth's climate, with global warming (currently more than 1.0˚C above pre-industrial levels) as the most widely known consequence. Climate change will have wide-ranging effects, including on human health, and the World Health Organization even considers it 'the biggest health threat facing humanity' in the 21st century.[20] The human health effects of climate change have been relatively well studied, as illustrated by the large number of systematic reviews published over the past twenty years (e.g., McMichael et al., 2006; Mora et al., 2018; Ebi & Hess, 2020) and synthesis reports (e.g., EASAC, 2019; IAP, 2022). However, as will be explained below, the relationships between climate change and human health are complex and likely encompass multiple direct and indirect pathways, some of which are already well documented while others are still less certain. There is also considerable uncertainty about the magnitude of the effects of climate change on human health.

The Intergovernmental Panel on Climate Change (IPCC) synthesises evidence of the impacts of climate change in its reports, the sixth and most recent of which was published in 2022. In terms of currently observable impacts on the world as a whole, it concludes that climate change has already adversely affected physical and mental health, in addition to having a negative impact on ecosystems, food and water security, urban infrastructure and some aspects of economic performance, and to contributing to humanitarian crises and population displacement. Specific health conditions mentioned as having increased as a result of climate change include heat-related mortality and morbidity, various infectious diseases and some forms of trauma (IPCC, 2022a).

This latest IPCC report also includes expert assessments of the likely future impact of ongoing climate change. For the medium to long term (2041 – 2100), and depending on the effectiveness of mitigation and adaptation actions, climate change is expected to cause escalating damage to human and natural systems, including further increases in heat-related mortality and morbidity, climate-sensitive infectious diseases, and mental health problems. Under a high-emissions scenario, experts expect over 9 million directly climate-related deaths annually worldwide by 2100,

20 https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

plus around 3.5 billion people living in contexts that are highly vulnerable to climate change, and therefore exposed to food and water insecurity, flood risk, displacement and poverty (IPCC, 2022a). The IPCC report does not comprehensively estimate the sum of all long-term health impacts of climate change.[21]

Another recent IPCC report evaluated progress towards the drastic reduction of greenhouse gas emissions necessary to limit global warming to 1.5°or 2.0°C, which is still considered relatively safe. Under current policies, and assuming that these would simply be continued into the future without extra measures being introduced, global warming is expected to amount to 3.2°C by 2100 (but could turn out to be more if climate sensitivity is higher than assumed) (IPCC, 2022b). A simple extrapolation of past trends in global temperatures also suggests the possibility of a sharper rise, i.e., around 4.0°C by 2100 (USGCRP, 2017). This would likely have very serious effects on human health, which can only be avoided if countermeasures are taken at a speed far exceeding the current pace of implementation.

At first glance, these alarming findings stand in sharp contrast to reports on the likely effects of climate change on health in the Netherlands. In the short and medium term, these health impacts are minor compared to those of, for example, smoking or obesity.[22] As mentioned above, the more favourable outlook for the Netherlands is partly because it lies in a temperate climate zone, and partly because it is assumed that its economic, technological and government resources will protect it against the more severe effects seen elsewhere. It is uncertain, however, whether the Netherlands will remain so well protected in the longer term. For example, although the increase in heat-related mortality will long be compensated for by a decline in cold-related mortality, a net increase in mortality related directly to temperature is expected by the end of this century (Hall et al., 2021). Furthermore, if global temperatures rise by 3.0 or 4.0°C, this may well lead to global disruptions on an unprecedented scale, potentially eroding the relative protection that high-income

21 The estimates mentioned in this paragraph are presented in Chapter 7 ('Health, Wellbeing and the Changing Structure of Communities') of the IPCC's *Impacts, Adaptation and Vulnerability* report (IPCC 2022a). The 'over 9 million' climate-related deaths are based on a single study capturing mortality related directly to heat and cold only, under a scenario implying a 4.0°C rise in mean global warming (Carleton et al., 2020). A more recent study, however, arrives at a much lower estimate, i.e., 2.2 million additional direct heat- and cold-related deaths worldwide under the same scenario (Burkart et al., 2022; but see Vicedo-Cabrera et al., 2022 for a critique of some of the methods of this as yet unpublished study). Quantitative estimates of deaths indirectly caused by climate change, e.g., through infectious diseases, malnutrition, flooding or forced migration, are currently lacking.

22 For a summary of the short- and medium-term health effects of climate change in the Netherlands, see also the website of the National Institute for Public Health and the Environment (RIVM) (https://www.rivm.nl/klimaat-en-gezondheid). A recent document setting out proposals for a research agenda addressing climate change and health also offers a brief overview of the state of knowledge for the Netherlands (Huynen et al., 2019).

countries currently enjoy (Sending et al., 2019). Finally, in the very long term, the Netherlands is highly vulnerable to the effects of sea level rise forecast to occur, particularly in high-end climate scenarios (the impact could be felt sooner if melting of the Arctic ice were to accelerate unexpectedly).[23]

Biodiversity loss and human health

The extinction rate of other living species is now one hundred times higher than before humans rose to prominence on planet Earth, and many remaining species are rapidly decreasing in numbers (IPBES, 2020). This loss of biodiversity is serious enough in itself, but there is growing recognition that it also poses immense risks to humans, as illustrated by recent reports on the economic and financial impacts of biodiversity loss (e.g., Dasgupta, 2021; Van Toor et al., 2020). These risks also extend to human health, but evidence that biodiversity loss affects human health is considerably less abundant and solid than evidence that climate change does. A limited number of broad-scope systematic reviews have been published, and their conclusions usually stress the provisional nature of the available evidence (Aerts et al., 2018; Lovell et al., 2014).

Nevertheless, there are good scientific reasons to be concerned about the risks to human health, because biodiversity is important for a range of 'ecosystem services' on which human health depends. Recent syntheses, e.g. by the World Health Organization and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), conclude that biodiversity is important for: (1) the availability of fresh water and clean air; (2) food production and nutrition; (3) microbial diversity in the human microbiome; (4) regulation of infectious diseases; (5) development of pharmaceuticals; (6) a 'genetic databank', which may in the future help humanity find solutions for a variety of problems; (7) mental and cultural well-being (WHO, 2015; IPBES, 2019; Martens & Beumer, 2015).

For some of these effects the evidence is relatively strong. For example, biodiversity loss may increase the transmission of certain infectious diseases. A systematic review concludes that biodiversity loss often increases infectious disease transmission (Keesing et al., 2010). Another relatively well-established pathway between

23 Chapter 9 ('Ocean, Cryosphere and Sea Level Change') of the most recent IPCC report *The physical science basis* presents estimates of the global mean sea level rise under different climate scenarios and on different time-scales. For 2100, it expects the global sea level to rise by 0.51 metres if global warming peaks at 2.0°C; by 0.61 metres at a peak of 3.0°C; and by 0.70 metres at a peak of 5.0°C. However, because melting of the Antarctic and Greenland ice sheets and thermal expansion of ocean water will continue long after peak temperatures have been reached, in the long run sea levels will rise much more. The IPCC expects that in 10,000 years, the global sea level will have risen by 6 to 7 metres if global warming peaks at 2.0°C; by 10 to 24 metres at a peak of 3.0°C; and by 28 to 37 metres at a peak of 5.0°C (IPCC, 2021; also see KNMI, 2021).

biodiversity loss and human health is through pollination and food production: declines in insect pollinators could lead to increases in non-communicable diseases and nutrient deficiencies (Smith et al., 2015).

Global pollution and human health

Environmental pollution at local and regional scales has been a long-standing issue of concern in public health, but as some forms of pollution have now reached all corners of Earth, there is a growing awareness that the scale and nature of the problem have changed significantly. Air pollution (mainly from burning fossil fuels) has become a worldwide problem that has major impacts on human health; many of the world's waters have become polluted (by industrial chemicals, pharmaceutical wastes, plastics, heavy metals, pesticides), and so have soils (e.g., as a result of the disposal of hazardous wastes). More generally, over the past century the chemicals industry has been turning out new chemicals at a very high rate, most of which have never been tested for toxicity but will in one form or another end up in the environment (Landrigan, 2020).

Many of the pollutants involved have potentially negative effects on the health of living organisms, including humans, and while some of these effects, such as those of air pollution, are well covered in the scientific literature, other effects are less well known, as illustrated by the following examples. Over the past decades, human sperm counts have declined considerably, contributing to reduced fertility. Although there is no consensus yet on the causes of this trend, 'endocrine disruption' from chemical exposures in prenatal life and exposure to pesticides in adult life have been implicated (Levine et al., 2017). Plastics from discarded packaging materials have entered ecosystems worldwide, and are now found in many animals as well as in many human foods, partly in the form of microplastics and nanoplastics. While there is legitimate concern over the possible risks to human health, sound evidence is still lacking (SAPEA, 2019).

Other global environmental changes and human health

Climate change, biodiversity loss and global pollution are the three environmental changes most commonly discussed as having a potential impact on human health. Other changes tend to remain in the background, partly because they are already implicated in climate change, biodiversity loss and/or global pollution to some extent. For example, land use change in the form of deforestation is an important contributor to biodiversity loss, and soil pollution may lead to loss of arable land. Nevertheless, these other changes have potential health effects that deserve separate attention.

Human activity has profoundly altered Earth's biogeochemical cycles of nitrogen and phosphorus. The use of artificial fertilisers has led to large amounts of nitrogen and phosphorus leaking into ecosystems, leading to eutrophication of lakes, rivers

and seas as well as land areas. Other sources of nitrogen overload are combustion of fossil fuels and manure from cattle breeding. The possible effects on human health have not been fully explored but are potentially serious, e.g., by making lake and river water unfit for drinking and by killing off fish (Tilman, 2020).

Human activity geared towards obtaining food, wood and many other resources from the land has also profoundly changed the surface of Earth. Prairies have been converted to cropland, forests have been cleared for pasture, dams have been constructed to block river flows, and built-up areas sprawl over what were once natural areas. These changes in land use and land cover have had positive effects on human health, but may also have negative effects through a variety of pathways. For example, deforestation may create greater opportunities for infectious disease transmission, and may indirectly threaten human health through accelerating climate change and biodiversity loss (DeFries, 2020).

Depletion of freshwater and arable land is also occurring on a global scale. Freshwater is essential for human health as well as for many human activities, but stocks are limited and demand is outpacing supply. Unsustainably high levels of water use (e.g., in the form of massive withdrawals from groundwater stocks for agriculture) raise the risks of water scarcity, which threatens human health both directly and indirectly (e.g., through crop failure or conflict). These risks are exacerbated by the climate change-induced melting of glaciers, from which many of the world's largest rivers spring. Unsustainable forms of agriculture are furthermore leading to a high rate of soil loss and soil degradation worldwide, threatening to reduce human food supply (Montgomery, 2020).

Pathways: direct, indirect and very indirect effects

Some of these environmental changes affect human health directly, others more indirectly, as illustrated by the examples given above. A useful distinction is between 'direct' or 'primary', 'indirect' or 'secondary', and 'very indirect' or 'tertiary' effects. In the case of climate change this distinction works out as follows. The direct effects on human health include the biological consequences of heat waves, extreme weather events, and other temperature-related changes such as interactions with air pollution. The indirect effects include health risks mediated by changes in biophysical and ecological systems, such as food yields, water flows, infectious-disease vectors, etc. The very indirect effects include more diffuse effects such as mental health problems in groups severely affected by the consequences of climate change, and the consequences of tension and conflict due to climate change-related declines in resources such as water, food and living space (McMichael, 2013).

This distinction is also relevant for other global environmental changes, although the balance between direct, indirect and very indirect effects may differ. Whereas direct effects are probably uncommon or even non-existent in the case of biodiversity loss,

they are very important in the case of global environmental pollution. But even in the latter, we need to distinguish between indirect effects (e.g., through reduced food yields) and very indirect effects (e.g., through competition for clean water). Although indirect and very indirect effects on human health are potentially more important than direct effects, the long causal chains involved often present a serious challenge for empirical research.

There are two common indirect pathways that link several of the global environmental changes to human health and are often studied in their own right because of their importance for Planetary Health: food production and consumption, and infection.

Food production and consumption, global environmental change and human health

Food plays a central role in the nexus between and around global environmental change and human health. On the one hand, food production and consumption are 'intermediate' between global environmental change and health, in the sense that global environmental change may harm human health by limiting humanity's options for producing nutritious food. For example, in the case of climate change the negative effects include agricultural productivity losses in tropical regions, a higher frequency of sudden food production losses due to extreme weather events and decreased fishery yields due to ocean acidification (IPCC, 2022a).

On the other hand, food production is also one of the main drivers of global environmental change: the need to feed a growing human population plays a crucial role in all the global environmental changes discussed so far. Agriculture makes a major contribution not only to greenhouse gas emissions and loss of habitat for other species but also to global pollution, land cover change and land degradation (Springmann et al., 2018).

This implies that changes in the production and consumption of food will be a crucial component of mitigation and adaptation strategies. The challenge is to provide a nutritious diet for a growing world population in the face of large-scale environmental degradation, while at the same time reducing the ecological footprint of food production. As part of the 'transformative' changes that this will require, Western diets (and dietary guidelines) will have to change drastically, in the direction of a more plant-based dietary regime. Fortunately, the alternative diets will also help prevent chronic non-communicable diseases (Tilman & Clark, 2014).

Infection, global environmental change and human health

Like food production and consumption, infectious diseases are a common pathway between several environmental changes and human health. Because changes in infectious disease transmission are among the more easily identifiable health effects

of global environmental change, they are relatively well documented, illustrating how human health still depends on ecosystem functioning, despite technological progress (Myers et al., 2013).

Although important progress has been made in our ability to prevent and treat infection, new infectious diseases keep emerging at a pace that appears to have increased in recent decades. Examples include Severe Acute Respiratory Syndrome (SARS, 2003), Swine Flu (2009), Middle East Respiratory Syndrome (MERS, 2012), Ebola (2013), Zika fever (2015), and COVID-19 (2019). Most of these newly emergent infections are zoonoses, which means that the pathogen first infects nonhuman animals and is then transmitted to humans, sometimes through vectors such as mosquitoes or other insects (Baker et al., 2022).

This implies that the risk of these infections depends on multiple factors, including frequency of contact between the organisms involved and the ecological conditions in which they live. The increased risk of newly emergent infections is probably due to a combination of increased contact between human and wildlife reservoirs (as humans move into previously uninhabited regions), increased contact between humans and domestic animals (as a result of changes in food production), and increased human 'connectivity' (as a result of urbanisation and globalisation). In the background, climate change may also play a role because it alters the geographical range of species and therefore induces novel interactions between species (Baker et al., 2022).

More generally, and not limited to newly emergent infections, climate change has been linked to a heightened risk of many infectious diseases among humans, including in world regions that were previously free of these diseases. There is substantial evidence of such effects on vector-borne diseases such as malaria, dengue, chikungunya, tickborne encephalitis and Lyme disease, and water-borne diseases such as cholera and other gastrointestinal infections (IPCC, 2022a).

Biodiversity loss is also thought to be associated with increased infectious disease transmission, e.g., through a decline in alternative hosts for the pathogen. Although the mechanisms are not yet well understood, empirical evidence suggests that biodiversity loss can indeed increase the transmission of Hantavirus disease, Lyme disease, malaria, schistosomiasis and West Nile Fever (Keesing et al., 2010).

This implies, among other things, that advances in infectious disease control are an important component of adaptation strategies to counter the adverse effects of climate change, biodiversity loss and other global environmental changes.

2.2 Drivers of global environmental change

Population and consumption

The environmental changes mentioned above have been caused, in one way or another, by human activity, i.e., by a combination of growing population numbers and increasing consumption per capita.[24] Because the growth of the world's population has not kept pace (in relative terms) with the increase in per capita consumption (as measured by GDP), it is often assumed that rising consumption levels are the most important of the two. Nevertheless, without population growth, rising consumption levels would have had a much smaller environmental impact, so the two should be considered in tandem.

The growth of the world's population, from around 1 billion in 1800 to 8 billion in 2022, is the result of the 'demographic transition', in which declining mortality preceded declining fertility (Chesnais, 1992). More recently, declining fertility has slowed population growth, but the world's total population is still increasing and expected to peak at 9 billion or more during the 21st century (Vollset et al., 2020; UN, 2022). The explanation for the decline of mortality and fertility is complex, and it is beyond the scope of this report to review the relevant literature. However, it is important to note that efforts to improve human health, e.g., in the form of public health programmes, have also played an important role (Mackenbach, 2020), suggesting that through its impact on population numbers, health care has unintentionally contributed to global environmental change.

Increases in consumption per capita, and in the associated use of energy and materials (water, food, minerals and so on), have been even larger in relative terms than increases in population numbers: global GDP per capita (in real terms) rose from around $1000 in 1800 to almost $15,000 in 2020.[25] Again, the explanation for these changes is complex, including factors ranging from humanity's age-old drive to eliminate hunger to the emergence of a modern consumption culture, and from technological innovations to commercial interests. However, while this economic growth has contributed to improvements in the quality of human life and longevity, it has also led to global environmental change, through greenhouse gas emissions, destruction of the habitats of other living species, chemical pollution and so on. Per capita rates of consumption of energy and materials are high but relatively stable in the developed world and rapidly rising in large parts of the developing world. Worldwide declines in consumption appear unlikely in the foreseeable future (Engelman et al., 2020).

24 A common way to conceptualise this relationship is the I=PAT equation, in which environmental impact I equals the product of population size P, affluence level A, and technologies used for consumption T. See, e.g., Ehrlich & Holdren, 1971.

25 On historical trends in world GDP, see, e.g., https://ourworldindata.org/

The role of health care

Many economic sectors are typified by high throughput of energy and materials. That is certainly true of the health care sector, suggesting that the production and consumption of health care have made a direct contribution to global environmental change. This suggestion has been confirmed by analyses of the ecological footprint of health care, which is estimated to be 1 to 5% of the total ecological footprint of human activities on Earth, but with wide variation between countries (Lenzen et al., 2020).

Estimates of the total ecological footprint of health care combine various environmental impacts, often in somewhat arbitrary ways. For a better understanding, it may be useful to look at specific environmental impacts. For OECD countries, the carbon dioxide footprint of health care is estimated at about 5% of the total national carbon dioxide footprint, which is similar to that of the airline industry (Pichler et al., 2019).[26] Estimates of health care's 'biodiversity footprint' arrive at similar percentages (Wilting & Van Oorschot, 2017). Increasing attention is also being paid to health care waste products that end up in nature, where they threaten not only human health (for example through drinking water) but also the health and survival of other living species. Critical substances used in health care that end up in nature are dioxins, mercury, latex, anaesthetics, antibiotics and hormones (Eckelman et al., 2018).

Because the Dutch health care sector accounts for a relatively large share of the economy, it also has a larger-than-average ecological footprint than that of other countries' health care sectors. A recent study has quantified five different footprints of the health care system in the Netherlands, expressed as a proportion of the total national footprint. It found that the share of the Dutch health care sector in the national footprint is 13% for material extraction, 8% for carbon dioxide emission, 7% for blue water consumption, 7% for land use and 4% for waste generation (Steenmeijer et al., 2022).

2.3 Strategies to avert global environmental change and its health effects

Mitigation and adaptation policies

There is general agreement that limiting the negative effects of global environmental change will require both mitigation and adaptation policies. Whereas mitigation aims to limit or reverse global environmental changes as such, adaptation aims to limit the negative effects of those changes that cannot be, or have not been, mitigated. This

26 Worldwide, greenhouse gas emissions from the health care sector are rising, and the health care sector now accounts for 5.2% of all greenhouse gas emissions (Romanello et al., 2022).

will be illustrated here for two global environmental changes: climate change and biodiversity loss.

In the Paris Agreement on climate change, adopted in 2015, countries have agreed to keep the rise in mean global temperature to well below 2.0°C above pre-industrial levels, and preferably restrict the increase to 1.5°C so as to limit the negative impacts of climate change, including those on human health. In order to achieve this goal, worldwide greenhouse gas emissions need to be reduced quickly and reach net-zero by 2050. It has been shown that this is theoretically possible by implementing a combination of mitigation measures, including a radical 'energy transition' from fossil fuels to wind, solar and other renewable forms of energy, changes in diet, carbon capture and storage, etc. However, worldwide greenhouse gas emissions continue to rise and the world is not on track to achieve the goals of the Paris Agreement and therefore avoid further negative impacts of climate change (IPCC, 2021). This is because mitigation policies are not being implemented quickly enough (Watts et al., 2021; UNEP 2022).

It will therefore be necessary to develop and implement effective adaptation policies as well, and to increase societies' resilience to a wide range of climate scenarios. Adaptation policies will need to address a broad spectrum of climate risks, and may involve creating early warning systems for weather-related disasters, building protective structures against flooding, improving buildings to keep them cooler, breeding crops for better drought or heat resistance, etc. Although the scientific literature on adaptation responses is growing rapidly, evidence of their effectiveness is very limited, and implementation is generally slow (Berrang-Ford et al., 2021).

Since the 1970s, various international agreements have also been made to slow the loss of biodiversity. The most comprehensive is the 1992 international Convention on Biological Diversity, which has been signed by most countries. In 2010, specific targets to be achieved by 2020 were added, e.g., halving the loss of natural habitats, reducing environmental pollution and removing invasive alien species. The latest monitoring report has shown, however, that virtually none of these targets were met in 2020, mostly because insufficient action had been taken (SCBD, 2020). In 2022, a new Global Biodiversity Framework was agreed along with a new set of ambitious targets for 2030.[27]

Intensification of biodiversity-conserving policies is considered essential to reverse the trend of biodiversity loss, including a radical transformation of food production and consumption, effective action to combat climate change, and substantial

27 A summary of the The Kunming-Montreal Global Biodiversity Framework can be found at: https://prod.drupal.www.infra.cbd.int/sites/default/files/2022-12/221219-CBD-PressRelease-COP15-Final_0.pdf

expansion of nature reserves and restoration of wild nature (Chan et al., 2020). A recent analysis shows that only immediate intervention on an unprecedented scale can reverse the curve of biodiversity loss around the middle of the 21st century (Leclère et al., 2020). This suggests that mitigation is unlikely to be fully successful, and it is therefore important to also develop adaptation strategies, e.g., to limit the effects on human health through increased infectious disease transmission or reduced food supply.

Mitigation and adaptation policies are likely to have important effects on human health, both intended and unintended, and these can be both beneficial and harmful in nature. Although net effects can be health-beneficial, it is important to know both sides so as to maximise positive effects and minimise negative effects. As this discussion has so far focused on climate change, it can serve as an example. Mitigation policies are expected to have important 'health co-benefits', e.g., owing to a reduction in air pollution (leading to less respiratory disease), more physically active modes of transport (leading to less cardiovascular disease), or less meat consumption (leading to less colorectal cancer) (Romanello et al., 2022). On the other hand, mitigation policies can also increase some health risks, e.g., because of improved housing insulation (leading to lower indoor air quality and associated health problems) (Ortiz et al., 2020), or exposure to wind-turbine noise (leading to sleep disturbance) (Schmidt & Klokker, 2014). In the same way, climate adaptation policies can have unintended 'health co-benefits', e.g., owing to more opportunities for physical exercise in greener cities, but can also generate more health risks, e.g., due to greater exposure to allergens in greener cities. With a careful mix of policies, however, the net effects of climate change mitigation and adaptation policies are likely to be health-beneficial (see, e.g., Staatsen et al., 2017).

Contributions of health care to mitigation and adaptation policies

It is widely acknowledged that health care professionals and health care institutions bear a special responsibility when it comes to the negative health impacts of global environmental change.[28]

28 A large number of manifests, alliances, organisations and scientific publications in medical journals testify to the sector's growing awareness of this responsibility. One example of an international alliance is Health Care Without Harm, which 'works to transform health care worldwide so that it reduces its environmental footprint, becomes a community anchor for sustainability and a leader in the global movement for environmental health and justice'; see https://noharm.org/. Another example, from the Netherlands, is the Green Deal on Sustainable Healthcare. This is a voluntary movement supported by the Dutch government that aims to reduce health care's carbon dioxide emissions and to achieve several other sustainability goals (Green Deal, 2022). Studies of health care's carbon footprint, sometimes even of individual health care units, are also booming; see, e.g., MacNeill et al., 2017.

One important contribution health care can make to mitigation policies is to reduce its own impact on the global environment. This idea has been taken furthest with regard to health care's greenhouse gas emissions. Life cycle analyses show that only around a quarter of health care's carbon footprint comes from the direct delivery of care, and that most comes from its supply chain, with additional contributions from staff and patient travel (Tennison et al., 2021). Initiatives to reduce health care's carbon footprint are being taken around the world, with an exemplary role for the UK's National Health Service, which is pursuing a target of 'net-zero' emissions by 2040. This implies 'decarbonising' the delivery of health care (e.g., by changing to other heating systems) and the supply chain (e.g., by procuring products from suppliers that are decarbonising their own processes) (National Health Service, 2020).[29] Additional strategies are needed to reduce health care's other global environmental impacts.

Another contribution health care can make to mitigation policies is to ensure that its health promotion activities are 'planet-proof'. An important example is dietary advice: traditionally, the health care sector has largely ignored environmental concerns in its dietary recommendations, e.g., to regularly consume fish or dairy products. More generally, health promotion activities could, in addition to getting people to smoke less and exercise more, aim to induce behavioural changes necessary to limit the future health impacts of global environmental change, e.g., promote '1.5-degree lifestyles' with less air and car travel and less meat consumption (Institute for Global Environmental Strategies, 2019). How to effectively induce such changes is, however, still unclear.

Health care will also have an important role to play in adaptation policies in that these aim to reduce the impact on human health. Given the inevitability of further climate change, it will be necessary to develop strategies to limit the health effects of more heat waves, more flooding, more infectious disease transmission and so on. Many countries have developed national adaptation plans to deal with heat waves, but in most cases without adequate funding (Watts et al., 2021).

Another important role for health care in adaptation is in countering the negative health effects of changes in infectious disease transmission. This includes pandemic preparedness, which is already relatively well developed for influenza but will need to be stepped up as part of adaptation policies, with elements such as improved surveillance systems, anticipatory vaccine and drug development and closer international collaboration. Non-pharmaceutical interventions (better

29 For a European perspective on decarbonisation of the health care sector, see EASAC/FEAM, 2021.

ventilation, face masks, remote working, etc.) will also be important.[30]

Implementation: individual and collective behaviour change and governance

Mitigation and adaptation policies not only depend on technological innovation but also require profound changes in the behaviour of citizens, commercial companies, public institutes and policymakers.[31] For example, citizens will need to switch to a more plant-based diet and to reduce car and air travel, but their knowledge of the relative impact of various changes in behaviour is still very limited. Although education is therefore important, large-scale change also requires changes to the systems shaping and maintaining individual behaviour, e.g., changing the availability and/or affordability of products by regulatory means, financial incentives, etc. (Marteau et al., 2021). There is also growing recognition that 'social tipping points' will be necessary, in which behaviour change by an initially small group of forerunners triggers behaviour change in the population at large, e.g., through the diffusion of new norms (Otto et al., 2020; Winkelmann et al., 2022).[32]

A similar reasoning applies to the 'behaviour' of commercial companies and other collective entities: these will often need to make profound changes to their operations to reduce their ecological footprint, which will likely require a combination of strategies ranging from mild economic incentives to strictly enforced regulations. One key to the timely implementation of mitigation and adaptation policies is therefore governance at subnational, national and international levels, e.g., by laws, regulations and other administrative processes. Climate laws and carbon pricing are examples of effective forms of governance supporting a reduction in greenhouse gas emissions, but policy packages combining different approaches are likely to be necessary to shift development pathways towards a zero carbon future. International cooperation will also need to be strengthened in order to increase political and macroeconomic alignment, and financial investment flows will need to be better aligned with environmental concerns (IPCC, 2022b).

30 See, e.g., https://www.who.int/initiatives/pandemic-influenza-preparedness-framework. For an analysis of the scientific underpinnings of pandemic preparedness, see the recent Academy report *Met de kennis van straks. De wetenschap goed voorbereid op pandemieën* (https://www.knaw.nl/publicaties/met-de-kennis-van-straks-de-wetenschap-goed-voorbereid-op-pandemieen).

31 Please note that throughout this report we use the term 'behaviour' in a broad sense, comprising not only the behaviour of individuals but also that of groups: companies, schools, hospitals, municipal authorities, national governments, etc.

32 'Social tipping points' should not be confused with 'physical tipping points', for example degrees of global warming beyond which melting of the Greenland ice cap becomes inevitable. For a discussion of the links between social and physical tipping points, see Franzke et al., 2022.

Transformative change

Because the drivers of global environmental change are so deeply embedded in the way human societies are organised, many analyses have pointed to the need for radical or 'transformative' change, defined, for example, as 'a fundamental, system-wide reorganisation across technological, economic and social domains'. Areas in which transformative changes are required include consumption and production (e.g., shifting to a circular economy), energy (e.g., decarbonisation), food (e.g., shifting to a more plant-based diet) and the urban environment (e.g., shifting to sustainable means of transport) (EASAC, 2020).[33]

Although the necessity of many of these changes is undisputed, as illustrated by the fact that similar lists of required changes have been included in many policy documents, it is less clear how they can be achieved. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) distinguishes five 'levers' (e.g., creating effective incentive systems, strengthening environmental laws) and eight 'leverage points' (e.g., enabling visions of a good quality of life that do not entail ever-increasing material consumption, ensuring environmentally friendly technological and social innovation). It also recognises important barriers to change (e.g., vested interests, limited capacity of governments to implement policies with timescales of decades, lack of public understanding) (IPBES, 2019; IPBES, 2021). Pleas for 'transformative' change often emphasise that achieving sustainability requires a fundamental change in the way the economy is organised, with a shift away from economic growth as conventionally defined. While the necessity of far-reaching changes is clear to all, however, there is no consensus on the exact nature of these changes, with viewpoints ranging from a belief in the possibility of 'green growth' (in which technological solutions make it possible to 'decouple' economic growth from environmental impacts) to a belief in the necessity of 'degrowth' (in which the consumption of energy and materials is radically downscaled).[34]

A further ramification of this discussion is that it points to the need to develop an integral vision for environmentally sustainable health care, one that goes beyond the specific roles of health care mentioned above and clarifies what level of health care will be possible 'within planetary boundaries' (Rockström et al., 2021). Analyses of the resource use associated with meeting human needs suggest that basic physical needs such as nutrition and sanitation can be met for all people worldwide without transgressing planetary boundaries, but that higher needs most likely cannot (O'Neill

33 The term 'transformational change' is often used as a synonym for 'transformative change'.

34 'Green growth' is a strategy promoted by many international organisations, such as the Organisation for Economic Cooperation and Development (OECD, 2011). For an explanation of the concept of 'degrowth', see, e.g., Hickel, 2020. For a systematic comparison and analysis of various viewpoints, see table 1 in Wiedmann, 2020.

et al., 2018). It is currently unclear whether, and if so, to what extent downscaling of health care activities (particularly in high-income countries) will be necessary if humanity is to stay 'within planetary boundaries'. This will inevitably also raise important ethical issues (Jameton & Pierce, 2001).

2.4 Conclusions based on the available evidence

The scientific literature clearly shows that global environmental change, in addition to having other detrimental effects, also has potentially negative effects on human health: current trends in the global environment even point to the possibility of disastrous long-term effects on human health worldwide.[35] Global environmental changes for which negative effects on human health are likely include climate change, biodiversity loss, global pollution of air, water and soils, altered nitrogen and phosphorous cycles, changes in land use and land cover, and depletion of freshwater and arable land. Although we lack quantitative estimates of the future impact of global environmental changes on human health (with the exception of climate change), the risks certainly appear to be considerable. Some of the pathways are partially known, with food production and consumption and infection playing a crucial role in the human health effects of several environmental changes.

Global environmental change is due to human activity, and driven by a combination of growing population numbers and increasing consumption per capita. Although specific mitigation and adaptation policies have been devised, and even agreed on in international treaties, their implementation has been slow. Transformative changes to society will be required to avert global environmental change and its health effects, but it is currently unclear what the ultimate direction of these changes should be. Health care makes a small but relevant contribution to global environmental change, and has an important role to play in both mitigation and adaptation strategies.

We must also conclude, however, that evidence of the human health effects of global environmental change is often incomplete and/or indirect, that pathways are insufficiently understood, that the effectiveness of mitigation and adaptation policies has not been firmly established so far, and that it is currently unclear how

35 Please take careful note of how this conclusion has been phrased. (1) It assumes extrapolation of 'current trends' without effective mitigation and/or adaptation policies. (2) Disastrous effects on human health are no certainty, but a possibility. (3) Although global environmental change is already having a negative effect on human health, much more serious effects are expected in the (sometimes distant) future. (4) 'Health' as understood here includes much more than (the absence of) disease, and extends to hunger, violence and other forms of human suffering that will show up in health statistics. (5) Some world regions are much more vulnerable to the health effects of global environmental change than others, and most of the health damage is expected to be inflicted on populations in the 'Global South'.

timely behaviour and policy change can be realised. In other words, knowledge gaps are many and deep. In the next chapter we report on our efforts to identify these knowledge gaps more precisely.

3. GAPS IN KNOWLEDGE AND PRIORITIES FOR RESEARCH

This chapter proposes a research agenda for Planetary Health, in three parts: (3.1) A longlist of knowledge gaps in Planetary Health. (3.2) Priorities for Planetary Health research, based on relevance for policy and time necessary to conduct research. (3.3) Conditions for Planetary Health research in the Netherlands. The final paragraph (3.4) presents some general reflections on the survey of knowledge gaps and the priority-setting exercise.

3.1 Longlist of knowledge gaps in Planetary Health

Previously published research agendas

In developing our research agenda, we started by examining four available inventories of knowledge gaps and/or open research questions for the field of Planetary Health:

1. The publication by the Rockefeller Foundation-Lancet Commission, published in 2015, which launched the concept of 'planetary health'. This contained a list of priority areas for research, based on an extensive literature review (Whitmee et al., 2015).
2. Ebi et al.'s paper on *Transdisciplinary research priorities for Human and Planetary Health*, published in 2020. The main research themes listed in this paper were identified during a participatory workshop organised under the auspices of the Future Earth Health Knowledge Action Network, held in Taipei in May 2019 and attended by 42 participants selected from an existing network on environmental health, consisting mainly of academics but also including some participants working for government or intergovernmental and non-profit organisations (Ebi et al., 2020).

3. The HERA (Health and Environment Research Agenda) project's *EU research agenda for the Environment, Climate & Health 2020 – 2030*. We worked with the final draft report published in September 2021.[36] HERA was a 36-month project funded by the EU Horizon 2020 programme that was launched in January 2019. It was carried out by a consortium of 24 partners, mainly institutes in the field of public and environmental health in EU countries. To create the research agenda, the consortium followed a structured approach consisting of a web-based survey among several hundred scientists to identify knowledge gaps, an analysis of policy documents, and a survey among several hundred policymakers to identify policy needs (HERA, 2021).
4. The National Science Foundation (NSF)'s report *Research priorities for Environmental and Human Health*, published in June 2021. The report was prepared by the NSF Advisory Committee on Environmental Research and Education, and was based on an online symposium exploring some of the research gaps that the COVID-19 pandemic had revealed. The report, which is based on consensus among the Committee members, sought to articulate key priorities for future research into the ways in which human and environmental health intersect and how best to respond to these impacts as a scientific community, effectively developing a Planetary Health research agenda (NSF, 2021).

These four reports were used to produce an initial inventory of knowledge gaps. Although the existing research agendas overlapped to some extent, one key finding at this stage was that there were also important differences between these research agendas in terms of how the field was structured conceptually and how completely they covered types of global environmental change and health impacts. We therefore started by creating a common conceptual structure, which also allowed us to start adding knowledge gaps identified in 'sectoral' publications, i.e., reports focusing on specific environmental changes (such as climate change or biodiversity loss), specific pathways (such as infectious diseases or food), or specific policy aspects (such as ethical or governance issues).[37]

The review of research agendas was mainly limited to agendas published in 2015 or later, and only included knowledge gaps falling within the above-mentioned boundaries of Planetary Health. The latter implied that in its explanation of the knowledge gap, the sectoral report had to make an explicit reference to one or more global environmental changes (i.e., climate change, biodiversity loss, global pollution, altered biogeochemical cycles of nitrogen and phosphorus, land use and land cover change, and depletion of freshwater and arable land), and that the proposed research

36 We used HERA's interim report as a basis for constructing the longlist of knowledge gaps. Since then, HERA's final report has been published (https://www.heraresearcheu.eu/hera-2030-agenda).

37 A list of the reports used for this version follows the longlist in the Appendix.

topic had to have a clear link with human health or its immediate determinants (such as nutrition or infection).

The 'upstream drivers' of global environmental change, such as the economic, demographic, social or cultural factors behind climate change or biodiversity loss, were considered beyond our scope, mainly because this is a huge field that can better be covered elsewhere. The same applies to the technical methods necessary for mitigation and adaptation strategies, e.g., for cutting greenhouse gas emissions or preventing floods. Such drivers or techniques were only included if there are knowledge gaps related to their impacts on human health.

This resulted in a draft longlist of knowledge gaps consisting of more than 100 specific knowledge gaps organised into almost forty more general research themes.

Constructing a longlist of knowledge gaps

The draft longlist was sent for consultation to around 120 experts in the Netherlands and abroad, including researchers active in a wide range of disciplines and policymakers. The Committee approached an equal number of national and international experts, not only those overseeing a substantial number of research themes in the draft longlist but also those with in-depth expertise in specific subfields. Experts were asked to review some or all of the longlist and offer suggestions for improvement by adding research questions that were missing, rephrasing or removing research questions or restructuring the list. We received eighty completed questionnaires from 88 experts (see details in Appendix 6), often with extensive comments, suggesting various changes and additions. Key experts in the field of Planetary Health were among the respondents, including authors of previous reports proposing research agendas. The respondents worked in the Netherlands (71) or abroad (17) and included researchers (58) as well as policymakers and professionals working in the field (30). The list of experts consulted can be found in Appendix 3; further details on the consultation can be found in Appendix 6 on the Academy's website.

Many respondents expressed their appreciation for the systematic way in which the longlist had been prepared, and indicated that its conceptual structure was clear and adequate. At the same time, some important suggestions for improvement were made, many of which were adopted after discussion in the Academy's Planetary Health Committee. These related to the place of ethical issues in the longlist (more elaboration and more emphasis needed), the balance between integral and 'reductionist' approaches (to allow for interdependency of global environmental changes), and the need for greater consistency across parts of the longlist.

There were also numerous specific suggestions for additions or changes in wording that helped to improve the longlist. Based on this expert input, a number of specific

knowledge gaps were added, for example on the health impact of extreme climate change scenarios, the development of climate-resilient health care, the design of national and international laws, and the analysis of historical precedents of transformative change. The wording of many passages was altered in response to expert comments, e.g., to clarify ambiguities or to make knowledge gaps more specific or more comprehensive.

Explanation and illustration of the longlist of knowledge gaps

The final version of the longlist can be found in Appendix 2 and can be downloaded as a separate file: https://www.knaw.nl/en/planetary-health. Each of the specific knowledge gaps has been illustrated by one or two verbatim quotes from source documents or expert comments, to make them more concrete. The references mentioned in these quotes also illustrate the wide range of sources used to compile the longlist. The longlist has 115 'specific knowledge gaps' organised into 38 'research themes', ranging from the impact of biodiversity loss on human health to developing effective strategies to deal with the role of infectious disease in global environmental change, and from developing effective strategies to change citizen behaviour to developing quantitative models to study the impact of global environmental change on health. The Academy does not in any way claim that this list is complete, and would like to see it used as a 'living document' that can be adapted when new knowledge and insights are gained.

The obvious conclusion that can be drawn from this *long*list is that the number of open research questions is indeed huge. It is perhaps not surprising that we lack scientific knowledge given the relatively recent emergence of this new field of research and the breadth of the topic at hand, but it is nevertheless worth emphasising how much is still missing. It is impossible to summarise the contents of the longlist in the main text of this report, and we will therefore highlight just a few examples of its rich contents using the diagram in Figure 2.

The knowledge gaps identified in the longlist fall within four main research areas, i.e.:

a. Understanding human health impacts of global environmental change. This area includes knowledge gaps of an 'explanatory' nature, such as impacts of climate change, biodiversity loss or global pollution on human health, and some of the common pathways linking global environmental change and human health, such as food production and consumption and infectious diseases. It also includes knowledge gaps related to the environmental impacts of the health care system itself, and 'explanatory' knowledge gaps of a more overarching or integral nature, such as the health impact of combinations of exposures. Because some but not all of these relationships have already been investigated in detail, the level of specificity is rather variable within this research area; for example, it is more specific for the impact of climate change than for the impact of biodiversity loss on human health.

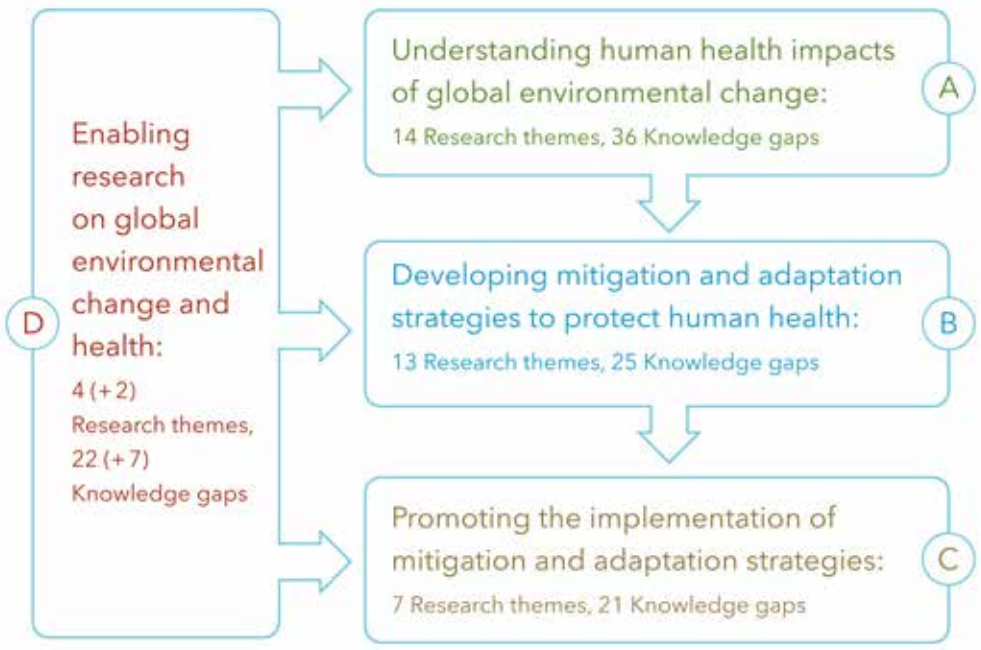

Figure 2. Longlist of knowledge gaps

b. Developing mitigation and adaptation strategies to protect human health against global environmental change. This area includes knowledge gaps related to the health impact of mitigation and adaptation strategies addressing climate change, biodiversity loss, global pollution and other global environmental changes. It covers such topics as the health co-benefits of phasing out fossil fuels, the development of diets which are both sustainable and healthy, improvements in infectious disease control and the development of climate-resilient health care systems. Like area A, it also includes a number of ethical questions, for example relating to equity and the interests of other living species.
c. Promoting the implementation of mitigation and adaptation strategies to protect human health against global environmental change. This area includes knowledge gaps of a more 'applied' nature, related to creating behaviour change among policymakers, professionals and the general public. It also includes research questions related to creating transformative change, developing effective modes of national and international governance, and designing effective national and international laws.
d. Enabling research on global environmental changes and health. This area includes recommendations with regard to data and methods in Planetary Health research, such as creating an adequate data infrastructure, developing new measurement and analytic methods and improving quantitative models. It also includes some

general recommendations on research practices and the training of scientists, such as the need for more interdisciplinary work, more science-policy dialogue, more participatory approaches (i.e., transdisciplinary), and changes in education. The latter are not strictly speaking knowledge gaps, but are seen as important conditions for Planetary Health research.

3.2 Priorities for Planetary Health research

Set-up of priority-setting exercise

To identify priorities for Planetary Health research, we invited a selection of experts to contribute to in-depth discussions on a specific sub-area. Six thematic groups were established: (1) Climate change and health; (2) Biodiversity and health; (3) Food production and consumption; (4) Infectious diseases; (5) Health care and public health; (6) Behavioural change and governance.

The experts were asked to rate longlist items on two criteria: (1) relevance for policy, i.e., degree to which research into the knowledge gap is necessary before effective policies can be pursued; (2) time necessary for conducting research and obtaining actionable results. They were also asked to rate the capacity of the Dutch research community to address the knowledge gap, in terms of both expertise and available technology.

This expert consultation was conducted in a 'semi-Delphi' set-up, in which experts first completed a written questionnaire individually and then participated in a group session in which they discussed summaries of the scores and their variation and were given the opportunity to adapt their scores in the light of arguments put forward by peers. Group chairs were instructed not to enforce consensus, but only to emphasise that any recommendations from the group based on consensus would carry more weight.

Participants in the priority-setting exercise consisted of a selection of respondents from the previous consultation round (see above) and a number of new experts. We strove for a 2:1 ratio between scientists and policymakers to allow for the 'demand' side in the process. Because one of the questions required in-depth knowledge of the Dutch research landscape, as well as on-site attendance of a group session, only experts based in the Netherlands were invited to participate. The total number of experts participating in this second round was 52 (of whom 35 were scientists, with 17 participants being employed by a policy-oriented organisation). Further details on the participants and the procedure can be found in Appendices 3 and 6.

Priorities based on policy relevance

This section reports on the main results for policy relevance, while the following sections cover the main results for 'quick wins' and for the capacity of the Dutch research community to address the knowledge gaps. Table 1 presents the specific knowledge gaps or research themes in each sub-area that scored very high on policy relevance. Here, we highlight three common threads in these results.

The most striking similarity between the six subgroups is that they all regarded research into behaviour change and governance as a top priority. It is perhaps no surprise that the expert group on behaviour change and governance did so, but it is remarkable that experts in other sub-areas, such as climate change or biodiversity loss, did so as well. Many experts believe that existing knowledge already provides sufficient evidence to take action against global environmental change and its health impact, but that most actors—citizens, commercial companies, public institutions and policymakers—are too slow in implementing effective policies. They expect that more research into determinants of individual or collective behaviour, or into the effect of behavioural interventions, or into the development of effective governance (including legal) mechanisms, will yield more valuable ways of promoting the implementation of mitigation and adaptation policies.

Table 1. Knowledge gaps (from the longlist) rated as top priorities based on their policy relevance

Expert group	The five top priorities	Number in longlist	Average rating
Climate change and health	• Integral analyses of global environmental change and health	A43	1.0
	• Health effects of climate change adaptation strategies	B113	1.6
	• Integral impact analyses of strategies addressing global environmental change and their health impacts	B41	1.6
	• Changing citizen behaviour	C11	1.7
	• Key drivers of global environmental change and health	A42	1.7
Biodiversity and health	• Impacts of biodiversity loss on health (general; explore mechanisms)	A121	1.1
	• Health impact of transformative changes to counter global environmental change and their health impacts	B43	1.2
	• Governance structures and practices to address global environmental change and health	C22	1.3
	• Health effects of biodiversity loss mitigation strategies	B121	1.3
	• Impacts of biodiversity loss on ecosystem services essential for human health	A122	1.4

Food production and consumption	• Integral analyses of global environmental change and health	A43	1.3
	• Effective policies promoting adoption of sustainable healthy diets	B213	1.3
	• Changing policymakers' behaviour	C12	1.3
	• Enabling transformative change to counter global environmental changes and protect health	C3	1.3
	• Governance structures and practices to address global environmental change and health	C22	1.4
Infectious diseases	• Effective prevention of emergence of infectious diseases related to global environmental change	B221	1.1
	• Changing policymakers' behaviour	C12	1.4
	• Integral analyses of global environmental change and health	A43	1.6
	• Health impact of transformative changes to counter global environmental change and their health impacts	B43	1.6
	• Changing citizen behaviour	C11	1.6
Health care and public health	• Legal instruments to address global environmental change and health	C21	1.1
	• Environmentally sustainable health care	B312	1.2
	• Enabling transformative change to counter global environmental change and protect health	C3	1.2
	• Changing health professionals' behaviour	C13	1.3
	• Health impact of transformative changes to counter global environmental change and their health impacts	B43	1.3
Behaviour change and governance	• Contextual approaches to changing citizen behaviour related to global environmental change and health	C113	1.0
	• Effective national laws to address global environmental change and health	C211	1.5
	• Effective international laws to address global environmental change and health	C212	1.5
	• Effective international governance to address global environmental change and health	C221	1.6
	• Understanding barriers to implementing policies addressing the health impacts of global environmental change	C122	1.8

Notes: The results of the individual expert groups cannot be compared directly because each group rated a somewhat different set of knowledge gaps. Letter/number combinations refer to items mentioned in the longlist (see Appendix 2). Average ratings of participants after group discussion, on a 5-point scale, with 1 indicating 'extremely important for policy' and 5 indicating 'not important for policy'. Items scored by less than two-thirds of participants have been omitted.

The second common thread is the repeated emphasis placed on 'integral' analyses. Several expert groups expressly pointed out the need for (more) integrated analyses, both within each sub-area (climate, food, infectious diseases) and across different sub-areas. Experts favour integrated analyses across the entire knowledge chain, i.e., from research into causes (section A in the longlist) to research into

countermeasures (B) to implementation-oriented research (C), because such an approach connects research as closely as possible with policy questions, allowing results to be more effectively transferred into policy. Many of them favour cross-field integration because global environmental changes are interrelated both in their causes and in their effects.[38] Only through integral analyses can we understand which changes will be necessary to effectively counteract global environmental changes and their health effects. Without integral analyses, there is, for example, a risk that measures aimed at mitigating one environmental change will unintentionally aggravate another. Conducting such integral analyses will be scientifically challenging and may require the development of mathematical models that can capture the whole causal chain running from global environmental change to human health.

The third common thread in the results for policy relevance is the emphasis on research supporting 'transformative' change. Many experts expressed the view that 'transformative' changes will be necessary to counteract potentially catastrophic environmental changes. This may well be correct, but it is important to note that the meaning of 'transformative' is open to interpretation. Sometimes 'transformative change' as understood by these experts implies a fundamental change within one subsystem (e.g. food, health care), but in other cases it implies a fundamental redesign of the entire economy or even society as a whole. Furthermore, the direction of such changes is often unspecified because there is no scientific consensus on what that direction should be. For example, a number of experts advocate a redesign of the economy whereby economic growth will no longer be the central aim, whereas others have high expectations of 'green growth', with economic growth being combined with lower throughput of natural resources. Nevertheless, we agree with the experts consulted that research in support of 'transformative change' should be prioritised, but it should also include more fundamental analyses of what types of changes are necessary and desirable and what their effects could be. The integral analyses mentioned above can play a role in thinking this through. Ethics and other humanities disciplines deliver important input because of the need to consider the foundations of human well-being and carefully weigh priorities.

Priorities based on quick wins

Table 2 presents, for each sub-area, the specific knowledge gaps or research themes that experts believe can rapidly be filled, i.e., for which the time necessary to conduct

38 It may be useful to distinguish between three different levels of integration. (1) A comprehensive analysis of the human health impacts of a single global environmental change requires integration across different health aspects. For example, in the case of climate change this requires taking into account heat stress, infection, malnutrition, etc. (2) A comprehensive analysis of the human health impacts of global environmental change in general requires integration across different types of global environmental change, also taking into account their interaction. (3) Finally, a comprehensive analysis of the impacts of global environmental change on the health of all life on Earth requires integration across different species.

research and obtain actionable results is relatively short. In view of the urgency of measures aimed at combating global environmental change, it is legitimate to prioritise research that would make policy more effective in the short and medium term, as opposed to research that will only pay off in the long term. As in the previous section, we will highlight a few common threads in the results.

Table 2. Knowledge gaps (from the longlist) that can be filled in the short or medium term

Expert group	Quick wins	Number in longlist	Average rating
Climate change and health	• Health-related prioritisation of climate change mitigation and adaptation strategies	B114	1.8
	• Changing health professionals' behaviour	C13	1.8
	• Impacts of climate change on health through extreme weather events	A111	1.9
	• Health effects of climate disaster risk management	B111	1.9
	• Impacts of climate change on health through sea level rise and river flooding	A112	1.9
	• Changing policymakers' behaviour	C12	1.9
Biodiversity and health	• Impacts of biodiversity loss on ecosystem services essential for human health	A122	1.5
	• Governance structures and practices to address global environmental change and health	C22	1.8
	• Key drivers of global environmental change and health	A42	1.8
Food production and consumption	• Guidelines for sustainable healthy diets	B212	1.1
	• Impacts of global environmental change on food insecurity	A211	1.4
	• Effective policies promoting adoption of sustainable healthy diets	B213	1.5
	• Governance structures and practices to address global environmental change and health	C22	1.5
	• Changing policymakers' behaviour	C12	1.6
Infectious diseases	• Integral impact analyses of strategies addressing global environmental change and their health impacts	B41	1.7
	• Enabling transformative change to counter global environmental change and protect health	C3	1.8
	• Health impact of transformative changes to counter global environmental change and their health impacts	B43	1.8
	• Effective non-pharmaceutical interventions against infectious diseases related to global environmental change	B222	1.8
	• Effective general response against infectious disease outbreaks related to global environmental change	B225	1.8

Health care and public health	• Health care's contribution to greenhouse gas emissions	A311	1.1
	• Sustainable health promotion practices	B322	1.4
	• Effects of public health interventions on global environmental change	A321	1.6
	• Sustainable sanitation and drinking water practices	B321	1.6
	• Changing health professionals' behaviour	C13	1.6
Behaviour change and governance	• Improving policymakers' understanding of health impacts of global environmental change	C123	1.0
	• Promoting implementation of sustainable health care practices	C133	1.3
	• Understanding barriers to implementing policies addressing the health impacts of global environmental change	C122	1.4
	• Determinants of institutional and policymakers' behaviour related to global environmental change and health	C121	1.5
	• Effective national governance to address global environmental change and health	C222	1.5

Notes: The results of the individual expert groups cannot be compared directly because each group rated a somewhat different set of knowledge gaps. Letter/number combinations refer to items mentioned in the longlist (see Appendix 2). Average ratings of participants after group discussion, on a 3-point scale, with 1 indicating '1 to 3 years', 2 '3 to 8 years' and 3 'more than 8 years'. Items scored by less than two-thirds of participants have been omitted. All items with an average score of less than 2 have been included in this table, with a maximum of five items per expert group.

The most striking finding is that knowledge gaps in area C (Promoting the implementation of mitigation and adaptation strategies) have most often been identified as possible 'quick wins'. Experts in all sub-areas believe that, by using existing social theories and by adapting existing techniques for individual and collective behaviour change, great strides can be made that may help to achieve policy goals for the global environment within the present decade. Experts in the sub-area of Behaviour change and governance agree. This is an important finding, because knowledge gaps in this area have also been rated high on policy relevance.

The second most striking finding is that many of the 'quick wins' concern knowledge gaps within the sub-area of health care and public health, broadly defined. This applies to a range of health care-related issues linked to global environmental change, from 'Health care's contribution to greenhouse gas emissions' to 'Changing health professionals' behaviour', and from 'Guidelines for sustainable healthy diets' to 'Effective non-pharmaceutical interventions against infectious diseases'. Although the role of health care in combating global environmental change and its health impacts may be relatively modest in comparison to other sectors, research investments are likely to produce relative quick actionable results.

Finally, it is important to note that not all experts wholeheartedly endorsed the view that research permitting 'quick wins' deserves priority: according to some, shortcomings in our current knowledge, for example in the field of global environmental change and the emergence of new pandemics, make investing in fundamental research a top priority, even if actionable results will only be obtained in the longer term. The Academy agrees that both fundamental or strategic research and more applied or implementation-oriented research are necessary.

3.3 Conditions for Planetary Health research in the Netherlands

A common conclusion of all expert groups is that the Dutch research world is currently not well equipped to properly address issues in the field of Planetary Health, or even large sub-areas within the broader field (such as climate change and human health, food production and consumption and human health, or infectious diseases). Experts' ratings of the available expertise and research infrastructure in the Netherlands were modest for all sub-areas (see Appendix 6, Table A6.1).

Nevertheless, experts in all groups agreed on a common theme: there is great potential for world-leading Planetary Health research in the Netherlands, but at the moment both the research world and research funding are too fragmented. There is considerable discipline-specific expertise within each sub-area, often even world-class, but it is spread over different institutions, hindering effective transdisciplinary research on the links between global environmental change and human health. The absence of an informal research community gathered around Planetary Health also means that researchers in different disciplines do not yet understand one another's language. Experts therefore noted that it may be necessary to form broad interinstitutional and interdisciplinary consortia to be able to conduct internationally leading research in this field.

Responses to whether there is sufficient funding to research issues in the field of Planetary Health differed per sub-area. Experts in some sub-areas (e.g., food in relation to global environmental changes and health) agreed that there is plenty of funding, but that opportunities for integrative or interdisciplinary research are generally lacking. In other areas (e.g., the relationship between climate change and health), experts agreed that there are no financing options, or that conditions for obtaining funding (e.g., necessity of matching by industry) form a serious barrier. Options for obtaining long-term funding are also too limited.

Experts in all sub-areas agreed that there are currently inadequate funding opportunities for interdisciplinary research in the field of Planetary Health, because such research often involves large-scale investigations whose interdisciplinary

nature does not slot comfortably into existing disciplinary assessment criteria. This is an important finding because, as mentioned above, integral analyses have been rated as highly relevant to policy, but the necessary institutional conditions and financing options are currently lacking.

3.4 Reflections on the process

In both the first and second round of consultation, we found experts eager to contribute their ideas and ratings. Although the field of Planetary Health was still new to many, the problem statement inviting them to participate evidently reverberated broadly. Many experts also expressed their deep concern about global environmental change and its potentially catastrophic impact on humanity and other living species. This indicates that scientists are deeply interested in conducting research into the knowledge gaps identified in this exercise, and in seeking out opportunities to obtain the time and money needed to do so.

In most expert groups, research into behaviour change and governance was rated as being highly relevant to policy. It was therefore all the more remarkable that we had trouble mobilising experts for the priority-setting exercise in this particular sub-area. Perhaps experts in behaviour change and governance do not yet sufficiently identify with the concept of Planetary Health, or our explanation of the link between global environmental changes, health, and behaviour and governance was not clear enough for them. At a more general level, this again illustrates one of the main challenges of Planetary Health research, i.e., to effectively bring together the fragmented expertise in the Netherlands.

There was only a limited degree of consensus among the experts concerning the prioritisation of research questions for a Dutch knowledge agenda. For example, the scores on the scale for policy relevance were often distributed across three adjacent positions of the 5-point scale. It should be noted that the experts consulted came from diverse disciplines and research fields, and in the absence of an existing Planetary Health research community, they had never had the opportunity to develop a common vision before we asked them to contribute to the priority-setting exercise. While this may explain the limited degree of consensus, it nevertheless implies that the Committee had to assign its own weighting to the results of the expert consultation.

During the consultation procedure, we encountered two important criticisms. The first critical response, from several of the experts we consulted, was that they disagreed with our focus on human health. Two overlapping arguments played a role here, namely (1) the desire to also do justice to the legitimate interests of species other than humans, because nature has intrinsic and not only instrumental value, and (2) the idea that an exclusive focus on human interests is itself responsible

for the unbridled impact of humans on their natural environment, and that the existential threat of global environmental change can only be averted when humans can once again see themselves as part of an ecosystem. We will come back to this issue in Chapter 4.

A second criticism expressed by some experts is that dividing up research questions into a large number of very specific knowledge gaps may divert attention from the need to achieve comprehensive changes in the structure of society and the economy, which may be necessary to protect planetary ecosystems effectively. In the view of these experts, one way to counter these risks is for research programmes to allow leeway to ask broader and deeper questions, in particular about the drivers of global environmental change and about developing ideas for a different, more sustainable way of living. Although we note a lack of consensus about the direction of the necessary 'transformative' changes (see above), we agree that there is an urgent need for such reflections, supported by sufficiently integrative forms of research.

EXAMPLES OF KNOWLEDGE GAPS

The hidden environmental costs of health care (longlist items A311, A312)
The health care system makes a substantial contribution to global environmental change, but an important part of this contribution is hidden in its supply chain, i.e., in the materials and products used, ranging from medicines to single-use gloves and from food to CT scanners. Although progress is being made, there are enormous gaps in our knowledge of the greenhouse gas emissions, biodiversity footprints and other environmental impacts of the tens of thousands of items involved. In order to prioritise strategies for 'greening' the health care system, it is therefore necessary to systematically conduct Life Cycle Analyses of these materials and products. What are the materials and products with the largest combined environmental impact? Clearly, this is an effort whose efficiency depends on international collaboration and the active involvement of industry partners.

Energy transition, energy poverty and health inequalities (longlist items B411, A411, A511, C114)
Climate change is expected to widen inequalities in health within countries, and it is therefore important that climate change mitigation and adaptation policies are designed in such a way that they do not contribute to a further widening (e.g., by increasing energy poverty), but instead to a narrowing of health inequalities (e.g., by stimulating active forms of transport across the whole population). The current acceleration of the energy transition offers many opportunities for observational, experimental and modelling studies of the impact of these policies on the living conditions, health-related behaviours, and health and well-being of disadvantaged groups. For example: What is the current impact of energy poverty on people's food choices and other health-related behaviours,

and how should financial incentive schemes to accelerate the energy transition be designed to maximise the health co-benefits?

Optimising the global diet in times of planetary change (longlist items A211, A212, B212)
Diet is crucial to health; conversely, global changes, including climate change, will have a major effect on diets. The diets of the future must be sustainably produced, nutritious, safe and affordable. While many requirements for sustainable food production are already known, research is needed to translate these into optimal local diets taking into account the climate, the available natural resources and the demography of the region. For example: What would an optimal diet for Western Europeans look like? This implies research into the optimal animal and plant protein mix, investigating the role that new species (such as insects, bacteria and fungi) can play in food, studying the biochemistry of food processing to increase nutrient uptake, and optimising nutrient retrieval from food waste and sewers.

Nature-Based Solutions for health and well-being (longlist items B111, B112, B113, B121, B141)
Nature-Based Solutions (NBS) are living solutions to human problems, inspired and supported by nature. NBS protect, sustainably manage and restore ecosystems, thereby increasing biodiversity while at the same time providing human well-being benefits. Examples include planting trees in cities to reduce the effect of heat waves, restoring mangroves to provide coastal protection against flooding and switching to restorative agricultural practices. Although NBS potentially deliver a wide range of benefits, there is a significant lack of understanding regarding the conditions under which NBS would work, and especially what their social and health impacts are. For example: How does increased exposure of city-dwellers to nature affect the spread of infectious diseases? Can protection and restoration of primary forests be used to tackle the emergence of zoonotic diseases? What is the acceptability of NBS to different groups in society, and how do different groups use or interact with a particular solution?

Mitigating pandemic threats and adapting to their occurrences (longlist items B221, B222, B225)
Human population growth, more contact between humans and domestic and wild animals (including insects), and intensifying human connectivity lead to more frequent zoonotic infections and pandemics. Mitigation strategies to change these underlying factors may be difficult, and effective adaptation strategies will therefore be all the more important. For example: How can cost-effective infection surveillance and response systems for humans and wild and domestic animals be developed to prevent pandemics and reduce their impact? What is the role of non-pharmaceutical interventions in making societies more resilient to pandemics (e.g., ventilation, distancing, face masks, etc.)? Can generic vaccine and therapy concepts be designed that are effective against a range of emerging infections, and can they then be used to help societies adapt to the increased risk of pandemics?

Adverse impacts of climate change on health call for adaptation actions (longlist items B111, B113, B114)
The adverse impacts of climate change, for example extreme weather events (heatwaves, storms, lightning, floods, droughts) and gradual sea level rise, have already been exacerbated faster than previously predicted by scientists. Sadly, these climate change adversities are projected to become even more severe and frequent in the coming two to three decades, even under intense emission reduction trajectories. Some harm human health and well-being directly, while others have more indirect effects. These challenges require fast, massive and sometimes transformational adaptation actions, but research is needed to address several important knowledge gaps in this area. For example: How can disaster risk management, in the form of early warning systems and preparedness, be improved? How can health care systems best deal with the mental health risks of flooding and flood-related evacuation? How can food systems be made more resilient to drought?

Biodiversity, climate change and Planetary Health (longlist items A432, B121, B422)
Climate change and biodiversity loss must be seen as intertwined rather than as separate phenomena. Not only does climate change contribute to biodiversity loss, but biodiversity loss may also aggravate the impact of climate change, because intact forests and ocean habitats act as massive 'carbon sinks' that help to sequester carbon dioxide from the atmosphere. Protecting and restoring ecosystems, and maintaining biodiversity, can therefore help us reduce the extent to which climate change impacts human health, but a better understanding of the many interlinkages is needed. For example: What is the combined effect of climate change and biodiversity loss on the spread of infectious diseases? What are the health risks and health co-benefits of integral policies to mitigate climate change *and* protect biodiversity?

Urban Heat Action Plans: how to retrofit our cities to make them healthier (longlist items B141, C11 [C111, C112, C113])
More severe weather patterns are emerging. Year on year, Europe and the world are breaking heat records, and this can be particularly risky for humans living in urban spaces. Family and community dwellings, as well as schools, workplaces and other infrastructures, are often not well adapted to extreme heat. Developing urban heat adaptation plans will require a clear understanding of needs in different contexts. This requires transdisciplinary work involving different scientific disciplines (political scientists, engineers, behavioural scientists, epidemiologists, etc.) as well as engagement with different stakeholders and end users (local councillors, town planners, health care professionals, etc.). Research questions include: What are the most effective ways to build heat-resilient cities? What are the barriers and facilitators for adaptation measures against heat stress at different levels within the system, starting with individuals and families? What are effective implementation strategies?

The role of health care professionals in climate change mitigation and adaptation (longlist items A3, C1 [A31, C13, C111,C112, C113, C132, C133])
Millions of health care professionals across the planet consult with their patients every single day, hour and minute. Increasingly, health care professionals are aware of the impacts of climate change on the health of their patients and are motivated to do something about it. There is a set of behaviours that can have mutual benefits for individuals and the planet (e.g., reduction in red meat consumption), suggesting that it may be possible to combine promoting healthy behaviours with promoting ecologically sustainable behaviours. Exploring this further requires transdisciplinary research into such questions as: What actions by health care professionals would effectively help patients engage in behaviours that are mutually beneficial for their own health and the 'health of the planet'? How can health care professionals be supported in better enacting these new measures in their everyday practice (e.g., what knowledge, skills, motivation, etc. do they lack)?

Effective international governance to address global environmental change and health (longlist item C211)
While more than 1300 international environmental treaties are in force, their ties with health policies are still poorly understood. Likewise, the 17 Sustainable Development Goals (SDGs) launched by the United Nations in 2015 seek to protect human health (SDG No. 3) and call for an overall integrative and coherent policy approach to sustainability. Yet current policy practice shows that most global governance institutions still operate in silos. Linking and integrating global health policies and global and national policies on the global environment are hence critical areas for further research, with a view to both major scientific advancements and broad policy impacts. For example: Has the agreement on SDG No. 3 in 2015 had any effect on local or national health policies? Can international environmental treaties help advance local and national health policies? Conversely, can local and national health policies lend more systematic support to international environmental treaties?

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Global environmental change and its effects on human health

Global environmental change will have 'potentially disastrous' effects on human health worldwide

Our review of the literature clearly shows that climate change and other global environmental changes pose very serious threats to human health. In line with the relatively well-developed evidence base regarding the long-term effects of climate change, an overwhelming majority of the experts we consulted rated these effects as 'potentially disastrous for human health' worldwide in the year 2100 in the absence of effective countermeasures (Figure 3). Most experts also rated the potential future impact on human health of other global environmental changes, such as freshwater scarcity, biodiversity loss and global pollution of air, water and soils, as very serious, but many indicated that it was difficult to rank these because of the interconnectedness of all environmental changes.

Without effective mitigation and/or adaptation policies, global environmental change will in the long run pose very serious health risks to billions of people, through heat stress, infectious diseases, malnutrition, flooding, displacement, violence and other forms of human suffering that will ultimately show up in health statistics. The most serious effects will likely not be seen in high-income countries but in other parts of the world, where some communities (such as those living on low lying islands or in areas that become uninhabitable as a result of extreme heat or drought) will even face existential threats. Global environmental change is also expected to widen health inequalities within countries.

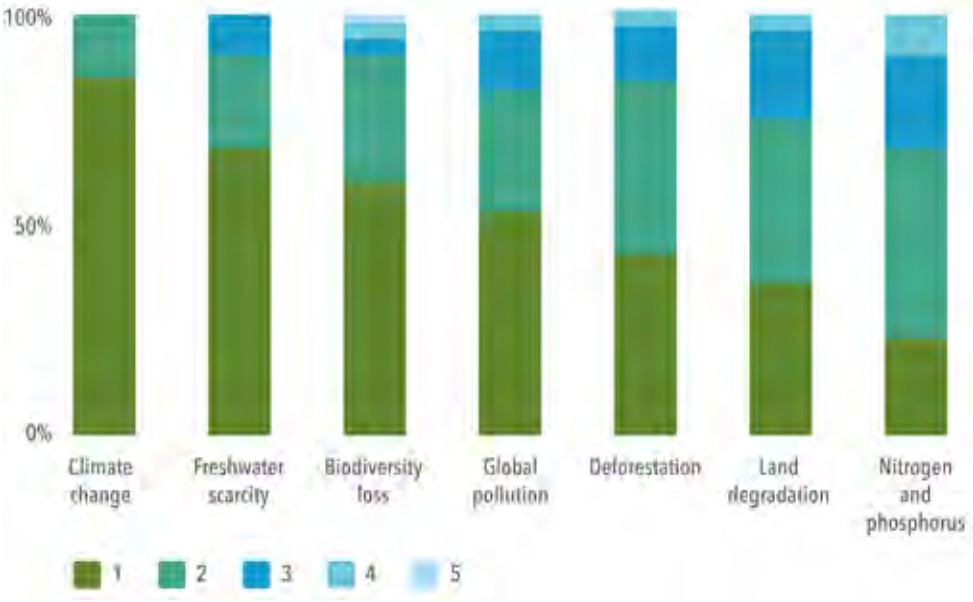

Figure 3. Potential future impact of global environmental changes on human health worldwide

Note: Percentages of respondents rating the impact on human health in the year 2100 worldwide, in the absence of effective countermeasures, on a 5-point scale, with 1 indicating 'high risk and/or high impact, potentially disastrous consequences for human health' and 5 indicating 'low risk or low impact, negligible consequences for human health'. Pooled results for six expert groups, excluding missings and question marks. Some experts divided their scores over two adjacent points on the scale.

Being relatively protected from the health impacts of global environmental change is no reason for high-income countries to be complacent. First of all, their historically large ecological footprints mean that high-income countries are largely responsible for the health effects of global environmental change elsewhere in the world. This implies, among other things, that research on global environmental change and health funded by high-income countries should not be limited to their own populations, but should have a worldwide scope. Second, there is no guarantee that high-income countries will remain protected in the future, particularly if the economic and/or political disruption caused by global environmental change destabilises the current world order.

Urgent action on global environmental change and its health effects is required, and positive outcomes are still possible

The Academy is deeply concerned about global environmental change and its consequences, including those for human health. Urgent action is required to avert these human health risks and other damage caused by global environmental change. Mitigation and adaptation policies should therefore be implemented without delay,

whenever there is a reasonable degree of scientific consensus on their effectiveness. If they are implemented rapidly, many of the detrimental effects of global environmental change can still be averted.

For climate change, mitigation strategies involving a society-wide transition to renewable energy sources have already been developed and agreed on in international treaties. If—and this is a big 'if'—these mitigation strategies are implemented rapidly enough, they will likely prevent truly dangerous global warming.[39] Together with effective adaptation strategies, this may well avert the most serious health consequences of climate change.

For some other forms of global environmental change, such as biodiversity loss, effective strategies are still at an earlier stage of development, and there is also less political commitment to mitigating these changes. Nevertheless, in principle the direction is clear. A combination of transformative changes in food production, effective action to combat climate change and a substantial increase in protected nature areas worldwide can stop biodiversity loss. It is still possible to avert the direst consequences, including those for human health—if timely action is taken.

Not only can 'potentially disastrous' consequences of global environmental change still be averted, but there is also the real possibility of net positive outcomes. Just like a 'green economy' does not need to be a poorer economy, a world without fossil fuels may well be healthier than the current one. For example, switching to renewable forms of energy will lead to less air pollution; switching to active forms of transport will encourage more physical exercise; and more energy-efficient buildings will help to reduce fuel poverty.[40]

Scientists and health professionals should speak out about the risks and advocate solutions in Planetary Health

With the threats being so serious and the pace at which countermeasures are being implement so slow, experts need to speak out loudly and clearly. The Academy is of the opinion that, although more research is required, it is even more important that scientists, both individually and collectively, actively communicate the risks of global environmental change and advocate effective countermeasures. Depending on the type of countermeasure, the available knowledge should be brought to the attention

39 IPCC 2022b, Mitigation. But please note that, while we know what concrete steps to take in the current decade, this is not yet the case for the following decades. Developing technologies and policies to reach 'net-zero' greenhouse gas emissions by 2050 will require a substantial investment in research.

40 IPCC 2022b. These and other health co-benefits of countermeasures can be used to create a positive outlook towards the future which, if more widely shared, may also improve the likelihood that climate change mitigation and other policies will be adopted.

not only of national and local governments, but also of public institutions, the private sector and the population at large.

Academies of science also have a role in these communication efforts.[41] The present report complements the Dutch Climate Research Initiative (KIN) established by the Academy and the Dutch Research Council (NWO), which includes mechanisms for close interaction with stakeholders.[42] The Academy intends to continue its engagement with policymakers on global environmental change, and will also explore whether and how to expand its direct communication to the general public.

Health professionals also have an important role to play. Currently, the health care sector does not yet have a strong voice in public debates on ecological sustainability. Now that the health risks of global environmental change are becoming increasingly clear, health professionals have a responsibility to add their voice to that of other experts and to explain that the transition to more sustainable patterns of consumption is necessary from a health perspective as well. The Academy calls on health care leaders to help achieve the societal changes necessary to avert the consequences of global environmental change. Health professionals may also want to explore whether and how advice on reducing one's ecological footprint can be added to their conventional health education messages on smoking, diet and physical exercise, for example.

4.2 Research agenda for Planetary Health

There are many important knowledge gaps in Planetary Health

Although decisive action can and should be taken now, more research is needed to further improve our understanding of the interlinkages between global environmental change and human health and to help develop and implement effective countermeasures. The Academy is aware that researchers always see scope for more research, but in this case it is needed to support urgently needed policies. In some areas more fundamental research is required, in other areas more applied research, but both fundamental and applied research on global environmental change and health should be 'mission-driven', i.e., focused on whatever can most

41 For example, the mission of the Royal Netherlands Academy of Arts and Sciences: 'The Academy promotes, supports and recognises excellent science and interprets the results of research for the benefit of society. The Academy articulates the importance of scientific research, knowledge and understanding for the economic, physical, social and cultural good and the well-being of mankind.'

42 The mission of the Dutch Climate Research Initiative (KIN) is to 'connect, deepen and expand climate-related research in the Netherlands with a view to accelerating system transitions, in collaboration with societal actors' (NWO/KNAW, 2022).

effectively contribute to the societal changes necessary to avert global environmental change and its health effects (Rathenau Instituut, 2021).

The Academy has identified a large number of open research questions in the field of Planetary Health and compiled these into a longlist of specific knowledge gaps (see Appendix 2). These knowledge gaps have been grouped into four main research areas: understanding the human health impacts of global environmental change (36 knowledge gaps), developing effective mitigation and adaptation strategies (36), promoting the implementation of mitigation and adaptation strategies (21). Furthermore, methodological and data issues need to be addressed to better enable research in Planetary health (22).

While we will not summarise this longlist here again, we wish to re-emphasise that many of these knowledge gaps impede effective countermeasures. For example, we do not know well enough where the health risks of biodiversity loss for human health lie, making it difficult to develop truly effective mitigation and adaptation strategies. We need to know more about the health risks and co-benefits of climate change mitigation and adaptation strategies so that they can be optimised and made more acceptable to the general population. We need to know more about the way in which the health care sector itself can become more ecologically sustainable, and about how to effectively change the behaviour of patients, medical practitioners and health care policymakers.

These examples cover just some of the specific health-related aspects of global environmental change. Many more knowledge gaps have been identified that have direct or indirect significance when it comes to safeguarding human health but are also relevant from a wider perspective. For example, although we know how to make food production and consumption more ecologically sustainable in principle (e.g., by switching to a more plant-based diet), we do not know how to achieve this effectively in practical terms. We also do not know how to create effective international governance mechanisms to avert global environmental change, or how to balance the interests of humans and other species in strategies to avert global environmental change.

Another important conclusion is that, although our inventory started with a focus on human health, many knowledge gaps can only be addressed with substantial input from disciplines other than the medical and health sciences. The full range of scientific disciplines (natural and life sciences, social sciences, humanities) must be involved. This applies, for example, to the impact of biodiversity loss on ecosystem services important for human health, to the analysis of intergenerational equity, to cost-effectiveness analysis of policies addressing global environmental change, and to understanding the barriers that policymakers encounter to implementing policies addressing global environmental change—to mention just a few. Many disciplines, from biology to law, from economics to meteorology, from virology to ethics, and from sociology to chemistry, have a role to play. Many issues will also require a

'transdisciplinary' approach, in the sense that research is conducted in collaboration with non-scientific and/or societal partners so as to make optimal use of their expertise and experience and create better conditions for the uptake of research results.

Finally, it should be emphasised that, as the most serious health impacts of global environmental change are expected to occur in the Global South, many of the knowledge gaps on the longlist will require research in and with low- and middle-income countries. This applies to issues ranging from the effects of extreme weather conditions on health to the development of effective vaccines, and from developing effective governance for biodiversity preservation to creating ecological health observatories in hotspots of disease emergence. Participation in Planetary Health research by scientists, practitioners and local communities in low- and middle-income countries is also essential to ensure the incorporation of local knowledge.[43]

Four priority areas for Planetary Health research have been identified

Based on expert consultation, the Academy has identified a smaller number of knowledge gaps in Planetary Health that deserve top priority because they are particularly relevant to policy. Some of these are also potential 'quick wins' because the time needed to conduct the research and obtain actionable results is estimated to be relatively short. The four priority areas are the following (with the first three presented in the same order as the longlist, i.e., moving from better understanding, to developing strategies, to implementation):

1. *Integral analyses of the effects of global environmental change on human health*. A better understanding of the risks to human health of global environmental change requires a more integrated perspective than most studies have so far used. We currently lack comprehensive estimates of the various risks to human health of each type of global environmental change; this requires integration across different health domains and pathways. We also lack comprehensive estimates of the risks to human health of combinations of environmental changes and their interactions; this requires integration across different types of global environmental change.[44] Integral analyses are also essential for a valid assessment of the effects of various mitigation or adaptation strategies on health, and for discerning the effects of global environmental change and countermeasures on health inequalities.

43 The importance of Planetary Health issues (in particular climate change, biodiversity loss and global environmental pollution) has recently also been acknowledged in the Dutch government's new Global Health Strategy (Ministerie BuZa & Ministerie VWS, 2022).

44 There is no comprehensive analysis of the impacts of global environmental change on all life on Earth. This would require integration across living species, a critical perspective if we want to balance the interests of humans with those of other species, e.g., when assessing the impact of various policies to combat climate change.

2. *Research guiding and supporting the transformative changes necessary to avert global environmental change.* To avert potentially disastrous environmental change, many sectors of the economy (energy, transport, food production and so on) will need to undergo transformative change. While the direction and final destination of these changes are relatively clear for some sectors (e.g., for the energy sector, where fossil fuels need to be replaced by renewable sources of energy), that is not the case for other sectors (e.g., health care, where it is currently unclear how ecological sustainability can be reconciled with quality and affordability). This implies that it is important to develop a comprehensive, evidence-based vision on what fundamental changes are needed and desirable in each sector, taking into account their intended and unintended health impacts. It is also important to study how such 'deep' changes can be achieved, e.g., by looking at historical examples of transformative change, or by analysing conditions for 'social tipping points', including the role that awareness of health risks can play.
3. *Research on methods for individual and collective behaviour change and governance in relation to global environmental change*. To prevent further global environmental change, behaviour change (including the 'behaviour' of collective entities such as private companies and public institutions) is urgently needed, as the current pace of change is too slow. Speeding up these changes entails applied research into the determinants of individual and collective behaviours driving global environmental change, and into the development of effective strategies to change these behaviours. Addressing the many knowledge gaps in this area will require the close involvement of the behavioural and social sciences, including psychology, economics, political science and law, in sustainability issues. Because health-related behaviours of citizens and the behaviour of health care professionals will also need to change, health psychologists and health promotion scientists will also need to get involved. Knowledge gaps in this area are not only highly relevant for policy but also represent potential 'quick wins' that can accelerate the implementation of effective mitigation and adaptation strategies.
4. *Research guiding and supporting mitigation and adaptation strategies for the health care sector*. To allow the health care sector to reduce its own ecological footprint, and to fully use health care's potential to contribute to adaptation strategies, the many knowledge gaps in this area also need to be addressed. They range from the health effects of extreme weather events to health care's contribution to greenhouse gas emissions, and from controlling infectious diseases related to global environmental change to guidelines for sustainable diets. Research into health care's ecological footprint will also require attention to sector's supply chains. Many of these research questions are not only relevant to policy but also represent potential 'quick wins', in the sense that research can build on existing data, methods and insights, and that results can inform health care policy and practice within the current decade.

All these priorities require interdisciplinary work, in which medical and health scientists collaborate with scientists from other disciplines, sometimes in a more leading role (e.g., for many knowledge gaps in research priorities (1) and (4)), sometimes in a more supportive role (e.g., for many knowledge gaps in research priorities (2) and (3)).

The challenges of Planetary Health necessitate new priorities within existing research programmes, and do not always require new funding

This research agenda will require more funding for research into global environmental change and health. In principle, funding can be increased in two ways: either by creating more funding opportunities within existing programmes (i.e., by setting new priorities), or by creating new programmes financed with additional money. Based on a rapid survey of funding opportunities for Planetary Health research in existing programmes,[45] the Academy is confident that at least some of the issues on the longlist of knowledge gaps can be addressed within existing national research programmes. Even without additional money, it will be possible to start up Planetary Health research in the Netherlands.

First of all, the Academy encourages Dutch researchers who have the relevant expertise to consider including questions related to Planetary Health in their own research plans. The fact that so many experts were eager to participate in our consultation rounds indicates that there is great interest in Planetary Health issues. Individual researchers are free to use the results of our inventory to develop grant proposals for various programmes run by the Dutch Research Council (NWO)[46] or other funding agencies. Existing opportunities have probably not yet been fully exploited.

Secondly, the Academy recommends that Dutch universities, university medical centres and non-academic research institutes should consider including questions related to Planetary Health in their own research programmes, for example by listing them as priorities for research development, or by using seed money from the 'first funding stream'[47] to encourage research in these areas. This applies in particular to the university medical centres (UMCs), which, despite their massive volume and expertise, are still largely absent from the field of

45 Appendix 7. Review of funding opportunities for Planetary Health research.

46 These include the Open Competition line, the Talent Programme (i.e., Veni/Vidi/Vici grants), the Dutch Research Agenda (NWA), and the Gravitation Programme and the Knowledge and Innovation Covenant. The National Growth Fund may also provide opportunities for Planetary Health research funding (see https://www.nwo.nl/financieringslijnen).

47 Dutch research funding is allocated through three 'funding streams' (*geldstromen*); for an explanation see De Jonge Akademie, 2022

Planetary Health research, as shown by a survey conducted in collaboration with the Netherlands Federation of UMCs.[48]

Thirdly, the Academy advises research funders to carefully evaluate their research priorities in view of these new risks to human health, which have not yet fully found their way into existing research programmes. The Dutch Research Agenda (*Nationale Wetenschapsagenda*, NWA) is an example of a research programme that already funds a number of projects on global environmental change, sometimes including health aspects, but the experts we consulted indicated that specific requirements for collaboration between public and private partners apply here, hindering Planetary Health projects. Several existing research programmes run by The Netherlands Organisation for Health Research and Development (ZonMw) could also create more room, within their current scope, for research on global environmental change and health.[49] The same applies to private research funding agencies in the Netherlands, such as the Health Funds (*Gezondheidsfondsen*) for various diseases, which may also want to consider the implications of global environmental change for their research priorities.[50]

New funding opportunities for Planetary Health research in the Netherlands will be necessary

Funding opportunities within existing research programmes will, however, not be sufficient: it is highly unlikely that all the knowledge gaps identified in this report can be addressed within these programmes.[51] This is even more true of the high-priority issues mentioned above. In our consultation round, experts indicated that it is often very difficult to obtain funding for interdisciplinary research, and that some areas (e.g., health care sustainability) even lack funding for straightforward 'monodisciplinary' research. Additional funding will be useful for another reason: it can be used to create a community of Planetary Health researchers, for example by making interdisciplinary and/or interinstitutional collaboration a requirement for participation in a Planetary Health research programme. Useful new funding opportunities might include the following:

48 For this survey, see Appendix 8 ('Planetary Health at the university medical centres in the Netherlands'). Although UMCs are far from the only parties to be involved in Planetary Health research, their expertise is relevant for many issues on the longlist of knowledge gaps.

49 One example is the ZonMw Health Promotion and Disease Prevention Programme (*Preventieprogramma*), which has a rolling budget and is renewed every four years, in agreement with the Ministry of Health, Welfare and Sports (https://www.zonmw.nl/nl/onderzoek-resultaten/preventie/gender-en-preventie/programmas/programma-detail/preventieprogramma-2019-2022/)

50 *Nederlandse Hartstichting*, *KWF Kankerbestrijding*, *Longfonds*, *Nierstichting Nederland*, etc.

51 It could even be argued that the sheer number of knowledge gaps shows that research funding is insufficient. Analyses in the literature have also pointed out a severe lack of funding for Planetary Health research; see Ebi, 2021.

1. NWO and the Academy are currently taking steps to implement the Dutch Climate Research Initiative, which includes a 'Pact' between all relevant parties and stakeholders, a virtual Centre for Climate Research (*Nationaal Centrum voor klimaatonderzoek*), and a research programme (NWO/KNAW, 2022). This initiative rightly recognises 'health' as an important dimension of climate research. The Academy encourages researchers in the medical and health sciences to participate actively in the Climate Research Initiative. It would also be mutually beneficial for the Initiative to adopt the climate-related research themes listed in the longlist of knowledge gaps as part of its research programme.
2. It would be helpful to set up a dedicated programme for Planetary Health research whose scope corresponds to the demarcation chosen in this report, i.e., aimed at better understanding the relationship between global environmental changes and human health, and at finding out how best to protect human health against these new threats. Within this scope, precedence could be given to topics falling within the four research priorities mentioned above[52] that often require an interdisciplinary and, sometimes, a transdisciplinary approach. A secondary aim would be to draw attention to Planetary Health issues among researchers from different disciplines, and to create a community of Planetary Health researchers who, after the programme has come to an end, can successfully apply for research grants in other, existing programmes. To ensure that the results will have maximum impact, central coordination and guidance will be essential, as in all 'mission-driven' research programmes (Rathenau Instituut, 2021).
3. Within the broader field of Planetary Health research, the ecological sustainability of the health care system itself merits special attention. Efforts to reduce the ecological footprint of the health care system are currently being hampered by a lack of knowledge in many areas. It would be beneficial to establish a dedicated fund supporting research into topics falling within the fourth research priority mentioned above, so that research necessary to fill these gaps can be scaled up.[53] This has also been recognised in the Green Deal on Sustainable Healthcare 3.0, recently signed by the relevant parties (Green Deal, 2022). The Academy therefore advises stakeholders, such as the Ministry of Health, Welfare and Sport

52 Meeting the objectives listed in this paragraph will require a budget of between €10 and €25 million, to be spent over a period of four to five years. This would provide funding for a few larger projects (between €1 and €3 million each, to be carried out by interdisciplinary consortia), a number of smaller projects (between €200,000 and €500,000 each), and a coordinator position (€100,000 per annum). These budget estimates do not include the cost of applied research into the ecological sustainability of the health care system, for which separate budgets will have to be set aside (see next point).

53 The knowledge gaps in this area have recently also been explored by ZonMw, the main funding agency for health research in the Netherlands. It has recommended a two-pronged approach: (1) incorporating ecological sustainability issues into existing funding programmes, and (2) setting up a dedicated programme to incentivise research into these issues (ZonMw, 2022).

and health insurance agencies, to discuss how financial support for health care sustainability research can be stepped up.

The urgency of the issues involved, the 'mission-driven' nature of the research and the relative inefficiency of conventional grant-giving procedures leads the Academy to advise funding agencies to consider using innovative ways of eliciting and selecting grant proposals, such as 'sandpits' and 'Lorentz workshops'.[54]

Filling all Planetary Health knowledge gaps requires an international collaborative effort in research funding

Implementing the research agenda will require the efforts of many scientists for many years. This implies that, while the Netherlands may want to step up its own research efforts in this area, it must also seek international collaboration to substantially boost the volume and depth of this research.

The European Commission already offers some funding opportunities for aspects of Planetary Health research.[55] It issued its first call for proposals explicitly dedicated to Planetary Health in early 2023.[56] This first call is, however, limited in magnitude. The same goes for research funding furnished by international philanthropic organisations.[57] The Academy will therefore bring its Planetary Health research agenda to the attention of international partner academies, and will discuss with international 'umbrella academies' (such as EASAC, FEAM and ALLEA) how to take this agenda forward. Several sister academies have already expressed an interest in

54 'Sandpits' are used by the UK Engineering and Physical Sciences Research Council and consist of intensive workshops involving both active researchers and potential users of research outcomes, aimed at creating innovative research proposals (https://beta.ukri.org/councils/epsrc/guidance-for-applicants/types-of-funding-we-offer/transformative-research/sandpits/). 'Lorentz workshops' have a similar set-up (https://www.lorentzcenter.nl/home.html) and have been recommended in the NWO/Academy Climate Research Initiative report (NWO/KNAW, 2022). Lessons learned working with alternative budget allocation methods in the Climate Research Initiative pilots will provide useful underpinnings for decisions regarding their wider application.

55 Appendix 7 contains a review of current funding opportunities for Planetary Health research.

56 See: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2023-2024/wp-4-health_horizon-2023-2024_en.pdf. As part of its dissemination efforts, the Academy has already shared the longlist of knowledge gaps with participants in an international workshop to discuss this upcoming EU call (see: https://www.isglobal.org/en/salud-planetaria).

57 Wellcome is an international funding agency with a dedicated programme for climate change and health (https://wellcome.org/what-we-do/climate-and-health). The Bill & Melinda Gates Foundation also takes an interest in the impacts of climate change, with an emerging interest in funding Planetary Health research (see, e.g., https://www.gatesfoundation.org/about/committed-grants?q=planetary%20health#committed_grants).

Planetary Health,[58] or in specific aspects thereof, such as climate change and health.[59] One option is to convene a meeting, under the academies' auspices, of national and international research funders to discuss an international collaborative effort to fund Planetary Health research, including the alignment of research agendas.

4.3 Planetary Health as a new field

'Planetary Health' was launched as a new field in 2015, and its boundaries are still somewhat fluid, as illustrated by the very broad definitions cited in Chapter 1. In this report we have developed an agenda for what appears to have become the core focus of Planetary Health research, i.e., to arrive at a better understanding of the relationship between global environmental changes and human health, and to explore how best to protect human health against these new threats. In this final paragraph, we broaden our view once again and present our conclusions regarding a few more general issues surrounding the emergence of this new field.

The new field of Planetary Health research is a valuable addition to existing fields of scientific enquiry, and deserves to be promoted and further developed

Planetary Health as demarcated in this report has two distinguishing features when compared to neighbouring fields of scientific investigation. The first is that its focus is on the effects of global environmental change *on human health*, and not on the economy or infrastructure, or on the health and well-being of other species. Although this may help to distinguish Planetary Health research from other fields within the broader domain of sustainability studies, this 'anthropocentric' focus has been criticised in the scientific literature because it seems to imply that impacts of global environmental change on humans are more important than impacts on other species (Lerner & Berg, 2017; Mackenbach, 2021). As discussed in Chapter 3, this criticism was shared by some of the experts we consulted.

Even so, a focus on human health is certainly useful for several reasons. Firstly, climate change, biodiversity loss, global pollution, deforestation and other global environmental changes are likely to have already had, and/or may in the future

58 Several national academies have expressed an emerging interest in Planetary Health, e.g., the German National Academy of Sciences Leopoldina (https://www.leopoldina.org/presse-1/pressemitteilungen/pressemitteilung/press/2900/) and the Royal Swedish Academy of Sciences (https://www.kva.se/en/event/policy-opportunities-for-reducing-climate-change-and-its-impact-on-planetary-and-human-health-2/).

59 EASAC has a long-standing interest in climate change and health (see, e.g., EASAC, 2019; IAP, 2022), and has issued a commentary, together with FEAM, on decarbonisation of the health sector (EASAC/FEAM, 2021). FEAM is broadening its interest in One Health to include aspects of Planetary Health (FEAM/IAP, 2022).

have, negative effects on human health severe enough to warrant dedicated research. Even if human health effects are not the main reason for introducing mitigation policies, they may be one of the reasons, and knowledge of human health effects is certainly a prerequisite for effective adaptation policies. Secondly, to counter global environmental change, large-scale behaviour and societal change is needed, and greater awareness of the health impacts may help to create the 'social tipping points' necessary for such change. Ultimately, risks to human health may be a more powerful motivator for change than other impacts, including those on other species.[60]

Nevertheless, the Academy fully agrees that human health is just one of the impacts to be considered. Global environmental change may also have negative effects on other human interests (e.g., damage to infrastructure or to the economy). Perhaps even more importantly, global environmental change also negatively impacts the health and well-being of other living species, many of which are even being threatened with extinction, and it may well be that focusing too much on human health will aggravate the risks for other species. Within the broader landscape of sustainability research, the mix of research programmes will therefore have to strike a balance between filling the knowledge gaps that relate directly or indirectly to human health, those that relate to other human interests, and those that relate to other species and the broader ecological context. Now that a research agenda has been developed for a relatively narrow concept of Planetary Health, it may be more feasible to develop a research agenda for a broader concept along the lines of some of the definitions found in the literature (see Chapter 1).[61]

The second feature which distinguishes Planetary Health research from neighbouring fields is that it potentially encompasses the whole range of global environmental changes (climate change, biodiversity loss, global pollution, freshwater depletion, etc.) related to every aspect of human health. While this is a tall order, and although it is too early to say whether this ambition can be realised, there are good scientific arguments for taking a broad perspective. We cannot paint an accurate picture of the effects of climate change on human health without looking at the interaction between climate change and biodiversity loss, air pollution and other environmental changes. We cannot develop a reliable estimate of the effects of global environmental change on human health by focusing on one or a few specific diseases only and ignoring compensatory or aggravating effects

60 See, e.g., Mogwitz et al. (2022).

61 But please note that even within the narrower concept chosen in this report, there is scope for studying impacts on other species in conjunction with those on humans, e.g., under the headings of 'integral analyses' (longlist research theme A43, Appendix 2) and 'Inter-species ethical issues' (themes A52 and B52). The necessity of monitoring other species should be emphasised in any dedicated Planetary Health research programme.

on other diseases. We cannot develop effective strategies to reduce the health impact of climate change if we ignore the side-effects arising from an aggravated biodiversity crisis or massive environmental pollution. Most specific studies within the field of Planetary Health will probably focus only on part of the picture, but Planetary Health as an umbrella concept will then help to integrate the results into a coherent whole.

Here again, it needs to be emphasised that Planetary Health is no substitute for closely related concepts such as One Health, EcoHealth or Environmental Health. Each of these cover areas that partly overlap with, but also partly lie outside the scope of Planetary Health. The Academy sees Planetary Health as complementary to these other fields. Collaboration will be essential to combine the energy and intelligence of these different research communities, which share a similar concern for ecological sustainability, into the force for change necessary to avert the potentially disastrous consequences of global environmental change.

In conclusion, Planetary Health research is a valuable addition to existing fields of scientific inquiry, and deserves being promoted and further developed.

Researchers and others interested in Planetary Health need to organise themselves

One of the conclusions of our expert consultation is that the Dutch research community is currently not well equipped to address knowledge gaps in Planetary Health. This is due not only to a lack of adequate funding opportunities, but also to a lack of interdisciplinary and interinstitutional collaboration. The absence of an informal research community gathered around Planetary Health also means that researchers in different disciplines do not yet understand one another's language.

More specifically, and in contrast to some other countries (e.g., the United Kingdom), Dutch medical and health research devotes very little attention to issues related to global environmental change and health. Lack of funding again plays a role, along with the relatively recent emergence of this new field. If this is to change, Dutch researchers will need to build expertise and form a scientific community. One good example is the related field of One Health, for which a network has been formed that brings together relevant expertise from different institutions and coordinates research on the relationships between human, animal and ecosystem health, particularly with regard to infectious diseases.[62]

The Academy therefore recommends that researchers interested in Planetary Health should form an interinstitutional and interdisciplinary network for Planetary Health research in the Netherlands. Such a network would support the exchange of

62 https://ncoh.nl/

expertise and serve as a springboard for collaborative grant proposals. Participation by policymakers would be important for linking research and policy and ensuring that research outcomes find their way into policy. In the same vein, a fully 'transdisciplinary' approach should be considered in which civil society organisations such as NGOs and citizen initiatives are also involved. If the research network were combined with a Planetary Health education network (see below), research findings would also more easily flow into education programmes. International collaboration will also be essential, both to bring scientific expertise currently not available to the Netherlands and to create opportunities for doing research in other parts of the world, particularly in low- and middle-income countries.[63]

Beyond research: Planetary Health should become part of tertiary education

The emerging field of Planetary Health is more than a new area of scientific inquiry. As several definitions emphasise, it also has a more action-oriented arm, in which public health practitioners and policymakers develop initiatives to counter global environmental change and its deleterious effects. While it is beyond the scope of this report to review these activities, let alone to make specific recommendations, the Academy has made one exception: it recommends making global environmental change, its potential impacts (including those on human health) and evidence of effective countermeasures an integral part of education programmes for professionals working in relevant sectors, including but not limited to health care, food and agriculture, urban planning and transport.[64] The establishment of dedicated minors, majors or complete Master's programmes in Planetary Health could also be considered. Incorporating knowledge gained in Planetary Health research and neighbouring fields into education programmes will ensure that it reaches those who can act on it. Many new initiatives

63 At the initiative of the Harvard T.H. Chan School of Public Health, a Planetary Health Alliance has been formed that brings together 'over 300 universities, non-governmental organizations, research institutes, and government entities from around the world committed to understanding and addressing global environmental change and its health impacts' (https://www.planetaryhealthalliance.org/). Recently, this global alliance created a European hub, of which the secretariat is based in the Netherlands and supported by an ad hoc consortium consisting of, among others, Maastricht University, Utrecht University/Utrecht University Medical Centre, VU University Amsterdam and Artis Amsterdam Royal Zoo. This illustrates that there is already a sound basis for network formation in the Netherlands.

64 This recommendation is meant for Dutch research universities and universities of applied sciences (*hogescholen*).

have already been introduced at separate institutions for higher education,[65] and these can be strengthened by more interinstitutional collaboration, for example joining forces to develop education materials, including materials for distance learning.

65 For example, based on a recent guide for planetary health education (Van Bree et al., 2022), new teaching modules on Planetary Health have been introduced in the medicine programmes at several university medical centres. This guide is partly based on an international consensus statement on Planetary Health education for health care professionals (Shaw et al., 2021). It is interesting to note that there is a burgeoning literature on Planetary Health education, some of which seeks to promote transformative societal change by introducing changes in education that go beyond simply adding elements of Planetary Health to existing curricula (see, e.g., Redvers et al., 2023).

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APPENDIX 1
RESOLUTION INAUGURATING THE PLANETARY HEALTH COMMITTEE

Having regard to Section 5.1 of the Academy's Regulations, the Academy Board has resolved to establish a 'Planetary Health Committee' (referred to below as 'the Committee').

Section 1. Remit of the Committee

The Committee's remit is to carry out an exploration the field. That remit is twofold:

1. to survey the situation: what is the current state of scientific knowledge regarding Planetary Health, what is already happening in the Netherlands and elsewhere in this field, and what knowledge gaps are apparent?
2. to draw up an—ambitious—agenda for knowledge development in the Netherlands in the field of Planetary Health: what opportunities are there for this field of science, both in terms of scientific content and with regard to facilities and cooperation (national and international), and how should these be prioritised?

Planetary Health is a new, interdisciplinary scientific approach to the relationship between human health and the health of the biophysical systems on which humans depend: what is the impact of the 'health' of the Earth on human health? This involves not only climate change and loss of biodiversity but also such things as large-scale environmental pollution, deforestation and land erosion, and other worldwide human-induced changes that entail new risks to health. Besides infectious diseases, those health risks also concern food and drinking water, migration and conflict, and mental health.

The COVID-19 pandemic provides an illustration of those risks: due to the increasingly intensive exploitation of nature, a new virus was able to leap from a bat to a human somewhere in Asia and—thanks to urbanisation and globalisation—that virus was then able to spread extremely rapidly across the globe. Despite all our progress—or perhaps because of it—we remain vulnerable. That vulnerability has changed over the centuries, but it has not disappeared. The 'Anthropocene' confronts us with new challenges. In order to identify the resulting risks, an integrated approach is needed.

That integrated approach is captured in the term 'Planetary Health'. In this interdisciplinary subject, in addition to the medical and health sciences, natural science disciplines such as biology and geology play a major role. The behavioural and social sciences are also needed, for example to fully understand the economic drivers of global environmental change, to understand behavioural change, and to resolve the governance issues involved in controlling Planetary Health risks. The humanities are also needed, among other things for proper historical analysis and for disentangling the ethical dilemmas that arise in balancing the many interests that are at stake.

This exploration adopts a broad approach to the subject of Planetary Health, with the aim of creating productive links between the disciplines involved and their knowledge agendas, and to ensure that the need for sustainability is reflected better —or even better—in the research priorities. The target group comprises knowledge institutions, bodies that fund research, and the Dutch Minister of Education, Culture and Science.

Section 2. Composition of Committee and Appointment Period

The following persons have been appointed (in their private capacity) to membership of the Committee:

Chair

Johan Mackenbach (Professor of Public Health, Erasmus University Medical Centre)

Members

- Vera Araujo Soares (Professor Health Psychology and Planetary Health, Twente University; as from 1 January 2023 Professor of Prevention, Heidelberg University)
- Lisa Becking (Associate professor Tropical marine biodiversity, Wageningen University)
- Frank Biermann (Professor Global sustainability governance, Utrecht University)
- Tatiana Filatova (Professor Computational economics, TU Delft)
- Ron Fouchier (Professor Molecular virology Erasmus University Medical Centre)
- Louise Fresco (Professor Food, agriculture and horticulture, Wageningen University)
- Pim Martens (Professor Planetary health, Maastricht University)
- Jan Luiten van Zanden (Professor Global Economic History , Utrecht University)

The Committee is appointed for the duration of the project involved. The Committee will submit its draft report to the Academy Board before 1 June 2022.

Professor Linda Steg[66] will serve as portfolio manager on behalf of the Academy Board. The Committee will receive support from Hanneke van Doorn and Maartje Aukes (both Academy Bureau) as secretary to the Committee.

Section 3. Quality and Integrity

Prior to the first meeting of the Committee, the members took note of the *Code to Prevent Improper Influence due to Conflicting Interests* [*Code ter voorkoming van oneigenlijk beïnvloeding door belangenverstrengeling*]; they confirmed having done so in a written statement. The Committee members familiarised themselves with the *Manual Concerning Academy Advisory and Exploratory Reports* [*Handleiding adviezen en verkenningen KNAW*], adopted by the Academy Board on 18 September 2017. The policy set out in that manual will be followed when assessing the draft advisory report.

Section 4. Work Plan

The Committee will draw up a work plan specifying its working methods and its communication and implementation strategy.

Section 5. Costs and Remuneration

The Academy will reimburse the Committee members for their travel expenses but will not make any other payment to them.

Section 6. Confidentiality

The Committee members will treat all information as confidential to which they become privy while implementing this resolution and which can be assumed to be such.

Adopted in Amsterdam by the Board of the Royal Netherlands Academy of Arts and Sciences on 16 February 2021.

On behalf of the Board of the Royal Netherlands Academy of Arts and Sciences,

M. Zaanen
General Director of the Royal Netherlands Academy of Arts and Sciences

66 In November 2021 professor Linda Steg stepped down as a member of the Academy Board. Professor Ton van der Steen succeeded her as a portfolio manager on behalf of the Academy Board.

APPENDIX 2
ACADEMY LONGLIST OF KNOWLEDGE GAPS IN PLANETARY HEALTH

The longlist can be downloaded as a separate file: https://www.knaw.nl/en/planetary-health.

Contents

Introduction

The longlist of knowledge gaps is based on existing research agendas published in 2015 or later and expert input from reviewers on the first draft of the longlist. It only includes knowledge gaps focussing on a better understanding of the relationship between global environmental change and human health, and finding an answer to the question of how best to protect human health against these new threats. The 'upstream drivers' of global environmental change, such as the economic, demographic, social or cultural factors behind climate change or biodiversity loss, were considered beyond our scope. The same applies to the technical methods necessary for mitigation and adaptation strategies, e.g., for cutting greenhouse gas emissions or preventing floods. Such drivers or techniques were only included if there are knowledge gaps related to their impacts on human health.

Knowledge gaps are structured into four areas, 15 subareas, and 40 broader 'research themes'. Each knowledge gap is illustrated by one or two literal quotes from source documents or expert comments. Subarea D2 includes some general recommendations on research practices and the training of scientists, which are not strictly speaking knowledge gaps.

AREA A: UNDERSTANDING HUMAN HEALTH IMPACTS OF GLOBAL ENVIRONMENTAL CHANGE

A1. SUBAREA: ASSESSING THE IMPACT OF GLOBAL ENVIRONMENTAL CHANGES ON HUMAN HEALTH

A11. RESEARCH THEME: CLIMATE CHANGE AND HEALTH

KNOWLEDGE GAP A111.

Impacts of climate change on health through extreme weather events

- Integrated research on the effects of extreme weather conditions on health and well-being (HERA)
- Research is needed to further knowledge of extreme weather and climate events on health, including injuries and illnesses, infectious disease emergence and spread, food security, and mental health, and on healthcare institutions, including the costs of impacts (Ebi)

KNOWLEDGE GAP A112.

Impacts of climate change on health through sea-level rise and river flooding

- There are a limited number of precise, quantitative studies of projected impacts of sea level rise at 1.5°C and 2°C, which particularly influence the human health, agriculture and water resources of small island nations (IPCC 1.5)
- Health impacts of flooding, not only coastal related to sea level rise but also inland from rivers and extreme precipitation events (expert input)

KNOWLEDGE GAP A113.

Impacts of climate change on health through working conditions and earning power

- The relative absence of evidence on the effects of [climate change on health through] agricultural shifts and livelihood instability...are also a concern (Berrang-Ford)
- [H]ealth effects of climate change through loss of earning power and workers' health deterioration (expert input)

KNOWLEDGE GAP A114.

Impacts of extreme climate change scenarios on health

- The health effects of climate change tipping points (e.g. sudden collapse of glaciers in Antarctica, slowing or cessation of the warm Gulf Stream in the Atlantic Ocean) (expert input)
- Research and modelling to understand the implications of 'high-end' climate change scenarios and nonlinearities (dangerous and irreversible tipping points), what might be the warning signals and time frames, and the various limits to adaptation (EASAC)

KNOWLEDGE GAP A115.

Impacts of climate change on under-researched health outcomes

- We found major gaps in evidence on climate health research for mental health, undernutrition, and maternal and child health (Berrang-Ford)
- Knowledge gaps on the health and well-being risks in the context of socio-economic and climate change at 1.5°C, especially in key areas such as occupational health (IPCC 1.5)

A12. RESEARCH THEME: BIODIVERSITY LOSS AND HEALTH

KNOWLEDGE GAP A121.

Impacts of biodiversity loss on health (general, explore mechanisms)

- To characterise the causal mechanisms by which (interactions of changes in) natural systems affect health (Lancet)
- Investigate how biodiversity supports the safeguarding of human health directly (through e.g. microbiome and related immunological benefits) and indirectly (through ecosystem services and related safety and security) in various contexts (HERA)

KNOWLEDGE GAP A122.

Impacts of biodiversity loss on ecosystem services essential for human health

- [T]he science linking biodiversity to ecosystem functioning and services must be extended to explore trade-offs between services at multiple temporal and spatial scales so that information can be incorporated into models of optimal land use (Cardinale)
- To assess threshold values for crucial ecosystem services, such as availability and access to food and water (Lancet)

A13. RESEARCH THEME: GLOBAL POLLUTION AND HEALTH

KNOWLEDGE GAP A131.

Impacts of specific aspects of outdoor air pollution on health

- [S]tudies of fine particulate matter in relation to respiratory and cardiovascular disease morbidity and mortality in adults. Recent years have documented in addition health impacts on reproductive health, neurological and psychiatric disease, and systemic impacts affecting children's and adults' health (HERA)
- European data on health effects and impacts of emerging or unregulated air pollutants, including ultrafine particles, air toxins, infectious and non-infectious micro-organisms, biological molecules (endotoxins, mycotoxins, and allergens), are largely missing (HERA)

KNOWLEDGE GAP A132.

Impacts of specific aspects of water pollution on health

- Assess health impact of plastic and specific contaminants in the marine environment and terrestrial water systems entering the food chain and their impact on human health (HERA)
- Assessment of human exposure to chemicals in drinking water, including frequently occurring pollutants and mixtures, also at low concentrations needs to be addressed to better evaluate health risks particularly in the long-term (HERA)

KNOWLEDGE GAP A133.

Impacts of toxic chemicals in globally distributed products, materials, and goods on health

- Assessment of the health impact of specific global pollutants, for example metals, persistent organic pollutants (POPs) and pesticides (HERA)
- [E]valuation of human health effects in large families of understudied chemicals (e.g. antimicrobial agents, flame retardants, food additives, pesticides, pharmaceuticals, plasticisers, surfactants, and other substitutes for additives to materials and goods) and health effects of endocrine disruption (HERA)

KNOWLEDGE GAP A134.

Impacts of microplastics and other small particles on health

- Little is known with respect to the human health risks of nano- and micro-plastics, and what is known is surrounded by considerable uncertainty (SAPEA)
- The impact of plastic micro-fibers and micro-beads (released through clothes laundering and the rinsing off of cosmetics and tyres) on human health (expert input)

KNOWLEDGE GAP A135.

Impacts of contaminated sites on health

- [C]ontaminated sites are well identified hot spots that remain a source of exposure to legacy compounds for decades and there is a need to identify … their impacts on human health (HERA)
- Environmental monitoring of contaminated sites and human biomonitoring/health survey of the population living in proximity to contaminated sites (HERA)

A14. RESEARCH THEME: OTHER GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

KNOWLEDGE GAP A141.

Impacts of specific aspects of urbanisation on health

- Assess the complexity and relationships between current urban transport and residential energy practices, exposures (air pollution, noise, heat island, excessive light and often lack of greenspace), and health effects and impacts (HERA)
- Very little research has been devoted to the subject of slum health… [Slums] remain invisible in many data systems…the evidence base in slum health is underdeveloped (Lilford)

KNOWLEDGE GAP A142.

Impacts of land degradation on health

- National monitoring efforts that directly collect subnational and perhaps household-level data are essential to our understanding of the impacts of desertification on human wellbeing (MEA)
- Understanding the impacts of desertification on human wellbeing requires that we improve our knowledge of the interactions between socioeconomic factors and ecosystem conditions (MEA)

KNOWLEDGE GAP A143.

Impacts of freshwater scarcity on health

- Research priorities [including the measurement and projection of] water supply quantity and quality stressors. Quantity stressors included shortage, drought, and water loss. Quality stressors related to industrial, agricultural, and other pollutant sources that lead to groundwater contamination and fecal pollution in watersheds (Setty)
- Among direct health impacts of water scarcity, physical and mental health [need to be] considered … water-borne diseases … carcinogenic diseases … skin diseases … mental health impacts (Paudel)

A2. SUBAREA: ASSESSING IMPORTANT COMMON PATHWAYS BETWEEN GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

A21. RESEARCH THEME: GLOBAL ENVIRONMENTAL CHANGE AND FOOD

KNOWLEDGE GAP A211.

Impacts of global environmental change on food insecurity

- Investigate the impacts of climate change and ecological change on resource security with emphasis on...effects on the food chain (HERA)
- Research is needed on the role of rising atmospheric concentrations of carbon dioxide, climate change, land-use change, and changing diets on the magnitude and pattern of food insecurity (Ebi)

KNOWLEDGE GAP A212.

Impacts of global environmental change on food quality and safety

- Research is needed on the linkages between biodiversity changes and...dietary diversity and health (HERA)
- Research also is needed on solutions to address reductions in food quality from higher carbon dioxide concentrations, and food safety from the increasingly industrialized production practices (Ebi)

A22. RESEARCH THEME: GLOBAL ENVIRONMENTAL CHANGE AND INFECTIOUS AGENTS

KNOWLEDGE GAP A221.

Impacts of global environmental change on exposure to infectious disease risks

- The ecology of biological agents, including the identification of pathogen reservoirs (e.g. animal species, soil, water, air compartments) and vectors both in rural and urban habitats, particularly where human populations and livestock live in close contact with wildlife and/or where human exposure and vulnerability is documented (HERA)
- Systemic research into the contribution of climate change to the emergence and spread of infectious diseases (HERA)

KNOWLEDGE GAP A222.

Impact of global environmental change on susceptibility to infectious disease risks

- Investigate how biodiversity supports the safeguarding of human health directly (through e.g. microbiome and related immunological benefits) (HERA)
- It is key to characterize the vulnerability of humans in terms of multiple exposure in rural, urban, occupational environments (HERA)

A23. RESEARCH THEME: OTHER COMMON PATHWAYS BETWEEN GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

KNOWLEDGE GAP A231.

Impacts of global environmental change on drinking water

- Investigate the impacts of climate change and ecological change on resource security with emphasis on water stress (HERA)
- Research is needed to anticipate the likely impacts of warmer temperatures and changes in the hydrological cycle on drinking water quality and quantity (expert input)

KNOWLEDGE GAP A232.

Impacts of global environmental change on conflict and migration

- [E]nhance the understanding of the role of environmental change in complex emergencies such as forced migration, conflict, and civil unrest (Lancet)
- Investigate the impacts of climate change and ecological change on resource security with emphasis on...population displacement and migration, including related health impacts (HERA)

KNOWLEDGE GAP A233.

Impacts of global environmental change on mental well-being

- Mental health impacts from changing biophysical conditions are also a growing research frontier...Many interdisciplinary questions in this area remain to be explored (NSF)
- [F]urther clarity and theoretical development of the concept [of eco-anxiety] is required to advance conceptual understanding of eco-anxiety...Future research could explore a much broader construct of eco-emotions and climate change-related mental health impacts (Coffey)

A3. SUBAREA: ASSESSING HEALTH SYSTEMS' CONTRIBUTION TO GLOBAL ENVIRONMENTAL CHANGE

A31. RESEARCH THEME: HEALTH CARE'S CONTRIBUTION TO GLOBAL ENVIRONMENTAL CHANGE

KNOWLEDGE GAP A311.

Health care's contribution to greenhouse gas emissions

- Pathway analyses of climate emissions from health care (Ebi)
- Development of a common model for calculating the carbon footprint for health (and social) care (expert input)

KNOWLEDGE GAP A312.

Health care's contribution to other global environmental changes

- Calculating the environmental costs and benefits of discrete components of [health care] activity, which could be used to build models for estimating the impacts of different options and pathways (WHO)
- The effects of production and consumption of pharmaceuticals on health, via waste water and other media (expert input)

A32. RESEARCH THEME: PUBLIC HEALTH'S CONTRIBUTION TO GLOBAL ENVIRONMENTAL CHANGE

KNOWLEDGE GAP A321.

Effects of public health interventions on global environmental change

- Address sustainability aspects [of sanitation and safe drinking water,] such as carbon footprint and waste products (e.g. brine from desalination) to quantify environmental impacts of treatment alternatives and personal drinking water choices (e.g. bottled water) to promote sustainable personal choices (HERA)
- Assess environmental risks and benefits of public health interventions, e.g. promotion of physical exercise and use of disposable face-masks (expert input)

KNOWLEDGE GAP A322.

Feedback effects of population health on global environmental change

- How does human health, including inequities in health metrics, consequences of poverty, and societal impacts of disease outbreaks, feedback to affect air and water quality, resource use, and biodiversity? (NSF)
- [T]he ways in which the current health status of a population – itself a function of age structure, diets, health care systems, degree of 'underlying health issues' and their distribution in a society, poverty, and inequality – contribute to global environmental change and/or shape its effects (expert input)

A4. SUBAREA: OVERARCHING ANALYSES OF HEALTH IMPACTS OF GLOBAL ENVIRONMENTAL CHANGE

A41. RESEARCH THEME: GLOBAL ENVIRONMENTAL CHANGE AND HEALTH INEQUALITIES

KNOWLEDGE GAP A411.

Impacts of global environmental change on the health of vulnerable groups

- Identifying, elucidating and quantifying climate change effects on health with a focus on...vulnerable population groups (e.g. pregnant women, infants, elderly, and disadvantaged groups due to income or ethnicity) (HERA)
- Explore how the different risk-factors and their combinations (accumulation) in the [climate, environment and health] nexus affect people in different situations and how these factors and processes can produce and maintain social disadvantages and increase vulnerability. How does social disadvantage translate into environmental disadvantage (HERA)

KNOWLEDGE GAP A412.

Impacts of global environmental change on the health of different world regions

- Research on the climate impacts on human health have so far focused on global risks, with limited focus on regional risks and adaptation options at 1.5°C and 2°C (IPCC 1.5)
- The impacts of global and regional climate change at 1.5°C on...food distribution, nutrition,...are poorly understood, particularly for developing nations (IPCC 1.5)

A42. RESEARCH THEME: KEY DRIVERS OF GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

KNOWLEDGE GAP A421.

Health impacts of economic drivers of global environmental change

- [Rising] consumption has been underlined as a common mechanism of...climate change, biodiversity loss, overload of the nitrogen and phosphorous cycles, freshwater depletion, ...[and is also a factor behind many modern health problems] (expert input)
- The role of commercial interests (e.g. companies involved in fossil fuel extraction) in driving both climate change and human health deterioration (expert input)

KNOWLEDGE GAP A422.

Health-related impacts of global environmental change on the economy

- Quantifiable human health effects can be taken into account as part of the economic analysis that goes into the decision-making process for policies affecting the environment and natural resource use (expert input)
- Climate change will also impact on global networks (trade, travel, infrastructure, welfare economy, etc.), affecting human health in various ways (expert input)

A43. RESEARCH THEME: INTEGRAL ANALYSES OF GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

KNOWLEDGE GAP A431.

Impacts of global environmental changes on health (general, comparative quantification)

- How are accelerating anthropogenic changes to the Earth's natural systems – biodiversity loss, climate change, land use change, pollution of air, water, and soil, scarcity of resources, and altered biogeochemical cycles – threatening human health? (NSF)
- What is the scale of these threats? Which populations are at greatest risk and/or most vulnerable, and which dimensions of health are most impacted? (NSF)

KNOWLEDGE GAP A432.

Impacts of combinations of global environmental changes on health

- Assessment of interconnected pathways linking global environmental changes, e.g. environmental pollution, biodiversity loss, land-use change, climate change, …and their health impacts (HERA)
- How do the various direct and indirect impacts of global environmental change on human health interact? For example, will the likelihood or impact of emerging infectious diseases be stronger under conditions where people suffer from poor water and land quality? (expert input)

KNOWLEDGE GAP A433.

Complex interactions between natural and social systems involved in planetary health

- [S]ystems-based understanding of the interconnections and feedbacks [between natural and social systems and human health] to strategically address upstream drivers (Pongsiri)
- [U]nderstanding of how human-driven stressors, singly or in combination, lead to global and local environmental change and how this change affects human health (Pongsiri)

A5. SUBAREA: ANALYSING ETHICAL ISSUES RELATED TO GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

A51. RESEARCH THEME: 'INTRA-SPECIES' ETHICAL ISSUES

KNOWLEDGE GAP A511.

Ethical reflection on health inequalities related to global environmental change

- Identify inequalities arising from environmental factors and their interaction with social and economic factors as well as approaches and solutions to address these issues and environmental justice (HERA)
- Evaluate the ethical and philosophical context of production and consumption patterns including the health effects of over-exploitation of resources, unsustainable food production and land-use, environmental injustice, migration and social displacement (HERA)

KNOWLEDGE GAP A512.

Ethical reflection on intergenerational aspects of global environmental change and health

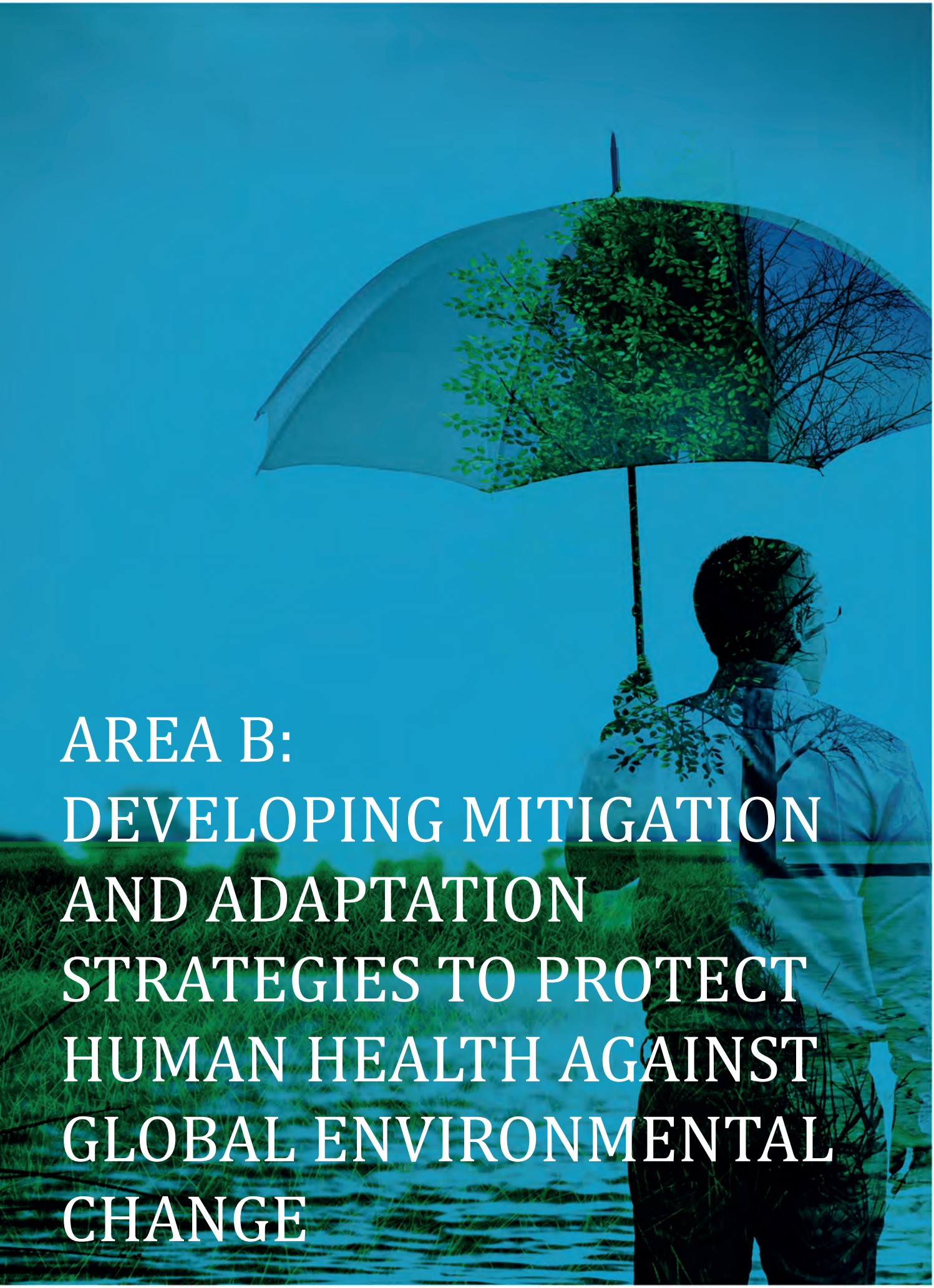
- Questions of intergenerational justice are becoming key issues for the millennial and later generations (expert input)
- Develop research models that address the issue of responsibility towards future generations (HERA)

A52. RESEARCH THEME: 'INTER-SPECIES' ETHICAL ISSUES

KNOWLEDGE GAP A521.

Ethical reflection on impact of global environmental change on other species

- The ethical implications of our moral responsibilities towards animals and ecosystems (expert input)
- Develop a vision on the value of the health of humans, animals and nature, and on how these different values can be weighed (Meijboom)



AREA B: DEVELOPING MITIGATION AND ADAPTATION STRATEGIES TO PROTECT HUMAN HEALTH AGAINST GLOBAL ENVIRONMENTAL CHANGE

B1. SUBAREA: DEVELOPING EFFECTIVE MITIGATION AND ADAPTATION STRATEGIES TO ADDRESS GLOBAL ENVIRONMENTAL CHANGES AND THEIR HEALTH IMPACTS

B11. RESEARCH THEME: CLIMATE CHANGE STRATEGIES AND HEALTH

KNOWLEDGE GAP B111.

Health effects of climate disaster risk management

- Research is needed to advance the practice of disaster risk management, preparedness, response, and communication, including through event forecasting and early warning systems (Ebi)
- Understand the effectiveness of social safety nets for reducing vulnerability to extreme events, and the effectiveness of adaptation strategies in reducing health risks, particularly in vulnerable communities and regions (Ebi)

KNOWLEDGE GAP B112.

Health effects of climate change mitigation strategies

- What are the side effects (positive and negative) of climate mitigation measures in the fields of energy, agriculture, care (Green Deal 2.0), sustainability (circular economy)? (ZonMw)
- What are the health effects of negative emission technologies (i.e. removal of carbon dioxide from the atmosphere) and geo-engineering (i.e. to reduce solar radiation) (expert input)

KNOWLEDGE GAP B113.

Health effects of climate change adaptation strategies

- Research also is needed to understand the...effectiveness of adaptation strategies in reducing health risks (Ebi)
- What are the positive and/or negative health effects of climate adaptation measures (e.g. heat-resistant building, blue/green spaces, artificial wetlands, changes in agriculture)? What are the long-term health consequences? (ZonMw)

KNOWLEDGE GAP B114.

Health-related prioritisation of climate change mitigation and adaptation strategies

- Which (mix of) measures are most desirable / cost-effective? (ZonMw)
- [T]he paucity of evidence on both climate change mitigation and adaptation (alone and in combination) is of great concern, and unless urgently resolved will greatly limit the ability of governments to design evidence-based pathways to reduce the effects on health of climate change (Berrang-Ford)

B12. RESEARCH THEME: BIODIVERSITY LOSS STRATEGIES AND HEALTH

KNOWLEDGE GAP B121.

Health effects of biodiversity loss mitigation strategies

- Explore policies (including e.g. land-use planning, intensified agriculture, forestry sectors, urban development, human security, sustainable economy, sustainable production and consumption) and their capacities to support health promotion, resilience, biodiversity conservation and restoration and multiple synergies (HERA)
- More research is needed to assess the health impact of nature-based solutions... Urban blue infrastructure... City trees... Green school playgrounds... Wildlife provisioning... Forest bathing... (Aerts)

B13. RESEARCH THEME: GLOBAL POLLUTION STRATEGIES AND HEALTH

KNOWLEDGE GAP B131.

Health effects of air pollution mitigation strategies

- Develop air pollution mitigation strategies to reduce risks of air pollution-associated diseases of European citizens in outdoor and indoor environments (HERA)

KNOWLEDGE GAP B132.

Health effects of chemical pollution mitigation strategies

- Research to optimise development of substitutes for hazardous chemicals through "Safe and sustainable by design" (HERA)
- Develop innovative technologies for minimizing contamination [of drinking water] by chemical mixtures and micro-/nanoplastics (HERA)

KNOWLEDGE GAP B133.

Health effects of environmental decontamination strategies

- Identification of targeted cost-effective actions for decontamination, prioritised on the basis of critical health impacts, and research to develop guidelines for urban planning related to the redevelopment of contaminated sites for new functions (HERA)
- Prevent and minimize exposures from food, feed and soil contamination and their negative impacts on human and animal health and ecosystem services, including new solutions for decontamination (HERA)

B14. RESEARCH THEME: STRATEGIES FOR OTHER GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

KNOWLEDGE GAP B141.

Health effects of urban sustainability strategies

- European cities are actively improving the urban environment through applying better urban planning (e.g. new urban models such as Superblocks, 15-minute city), better transport planning (increasing cycling lane length), nature-based solutions (e.g. planting trees) and EU initiatives (e.g. carbon neutral cities), but robust data is missing of the effect on environmental exposures (e.g. air pollution, noise, heat, excessive light), lifestyle factors (e.g. food consumptions, physical activity) and health effects (e.g. mental and physical health), and overall effectiveness (HERA)
- [W]e do not understand... what effect slum-focused health interventions could have... improved uptake of vaccination... which types of [sanitary] installation are suitable for which types of slum... effects on education, wellbeing, and productivity in addition to those on health (Lilford)

KNOWLEDGE GAP B142.

Health effects of land degradation mitigation strategies

- Quantitative and comparative analysis of land degradation avoidance solutions and restoration options [including impact on ecosystem services] (IPBES 2)
- More information is needed to assess the linkages between the policies for poverty reduction and combating desertification (MEA)

KNOWLEDGE GAP B143.

Health effects of improved water management strategies

- While new approaches [to water treatment] are constantly under development, consideration of the health impacts of pathogen reduction by various methods and degrees would help to support decision-making (Setty)
- Ensuring the sustainability of water supplies for increasing water demand requires holistic optimisation...[which] should be broadened to include resource use and health (JPI)

B2. SUBAREA: DEVELOPING EFFECTIVE STRATEGIES TO ADDRESS IMPORTANT COMMON PATHWAYS BETWEEN GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

B21. RESEARCH THEME: STRATEGIES FOR GLOBAL ENVIRONMENTAL CHANGE AND FOOD

KNOWLEDGE GAP B211.

Health effects of more sustainable food products

- [Assess nutritional quality of new] plant-based food products, including ultra-processed foods (WHO)
- Research is needed on risks, hazards and benefits of novel foods as well as people's perceptions and attitudes towards them and related technologies and solutions (HERA)

KNOWLEDGE GAP B212.

Guidelines for sustainable healthy diets

- Analyse and design what a sustainable European planetary health diet may look like (HERA)
- More research is needed to identify the most adequate healthy diets and their affordability and environmental sustainability across different contexts (UN)

KNOWLEDGE GAP B213.

Effective policies promoting adoption of sustainable healthy diets

- [Develop] food labelling covering both nutritional content and environmental sustainability, food profiling model for healthy and sustainable diets (WHO)
- [Develop] healthy digital food environments...this includes social media, online food retail, digital food marketing and food delivery apps (WHO)

KNOWLEDGE GAP B214.

Health effects of sustainable food production

- [Develop] ways to sustainably boost [food] production to meet current and future food demands, protecting and using biodiversity through biophysical and ecological practices, rapid reduction of the use of pesticides in intensive crop production, of antibiotics and steroids, and protecting the agriculture- and forest-related genetic base (UN)
- Explore sustainable agriculture and aquaculture to uncover the benefits and risks on food, diets and health, in relation to the synergies with climate adaptation and mitigation (HERA)

KNOWLEDGE GAP B215.

Health effects of strategies to reduce food waste

- [S]caling up sustainable cold chain technology to make perishable foods (especially vegetables and fruits; potatoes) more available and affordable and at the same time reducing food loss and waste (UN)
- Accelerating the reduction of food waste and loss calls for developing food processing refrigeration, storage and warehouse technologies (UN)

B22. RESEARCH THEME: STRATEGIES FOR GLOBAL ENVIRONMENTAL CHANGE AND INFECTIOUS AGENTS

KNOWLEDGE GAP B221.

Effective prevention of the emergence of infectious diseases related to global environmental change

- Obtaining and disseminating critical data on the wildlife trade and disease risk (IPBES)
- Assessing economic cost and benefits of preventing pandemics (IPBES)

KNOWLEDGE GAP B222.

Effective non-pharmaceutical interventions against infectious diseases related to global environmental change

- There is a clear requirement to conduct large, pragmatic trials to evaluate the best combinations [of non-pharmaceutical interventions] in the community and in healthcare settings with multiple respiratory viruses and in different sociocultural settings (Jefferson)
- The use of facial masks in the community setting represents one of the most pressing needs to address, given the polarised opinions around the world (Jefferson)

KNOWLEDGE GAP B223.

Effective vaccination against infectious diseases related to global environmental change

- Innovative research on human and animal Prophylactic Vaccines (NCOH)
- Development of vaccines requires investment in the entire chain from protective antigen discovery, vaccine production, vaccine delivery to efficacy studies requiring basic knowledge about immunity (NCOH)

KNOWLEDGE GAP B224.

Effective treatment of infectious diseases related to global environmental change

- Delineate the mechanisms of resistance to infectious agents in certain species and implication for human therapeutics (HERA)
- Development of broadly-reactive antiviral drugs (NCOH)

KNOWLEDGE GAP B225.

Effective general response against infectious disease outbreaks related to global environmental change.

- Analysing behavioural risk in communities, co-designing programmes to reduce risk (IPBES)
- [Develop] novel, generic approaches to disease and pathogen detection, and a collaborative approach to outbreak response (NCOH)

B3. SUBAREA: DEVELOPING EFFECTIVE STRATEGIES TO REDUCE NEGATIVE AND INDUCE POSITIVE HEALTH SYSTEMS' CONTRIBUTIONS TO GLOBAL ENVIRONMENTAL CHANGE

B31. RESEARCH THEME: STRATEGIES FOR GLOBAL ENVIRONMENTAL CHANGE AND HEALTH CARE

KNOWLEDGE GAP B311.

Climate-resilient health care

- Develop climate adaptation measures for the health care sector (expert input)
- Incorporate climate change effects on climate-sensitive health risks into health care policies (Ebi)

KNOWLEDGE GAP B312.

Environmentally sustainable health care

- Development of climate mitigation measures and sustainable technology for the health sector (HERA)
- How to reduce medical waste/ toxic waste/plastic waste (expert input)

B32. RESEARCH THEME: STRATEGIES FOR GLOBAL ENVIRONMENTAL CHANGE AND PUBLIC HEALTH

KNOWLEDGE GAP B321.

Sustainable sanitation and drinking water practices

- A paradigm shift is needed from waste being disposed of far away to resource recovery and reuse.... Similar transitions are needed for sanitation (Ebi)
- Quantify environmental impacts of [water] treatment alternatives and personal drinking water choices (HERA)

KNOWLEDGE GAP B322.

Sustainable health promotion practices

- Shifting priorities in behavioral medicine from the study of traditional behaviors (e.g. a volume of physical activity) towards the promotion of a behaviors with higher mitigation potential and adaptive behaviors embodied in a climate change context (Chevance)
- Include indicators for sustainability...when studying health behaviors to uncover their joint benefits for humans and the planet (Konig)

KNOWLEDGE GAP B323.

Effective family planning practices

- [A]ssess...population policy as a component of [climate change] mitigation or adaptation responses, as well as its costs and benefits, implementation barriers, and links to SDGs (Bongaarts)
- [The] practice of integrating access to family planning with natural resource conservation should offer fertile ground for evidence that the linkage works in the real world (Engelman)

B4. SUBAREA: INTEGRAL ANALYSES OF STRATEGIES TO ADDRESS GLOBAL ENVIRONMENTAL CHANGES AND THEIR HEALTH IMPACTS

B41. RESEARCH THEME: INTEGRAL IMPACT ANALYSES OF STRATEGIES

KNOWLEDGE GAP B411.

Effects on health inequalities of policies addressing global environmental change

- Assess potential economic impacts of mitigation policies on disadvantaged groups (HERA)
- More attention needed for the energy transition and associated health risks, e.g. related to fuel poverty (expert input)

KNOWLEDGE GAP B412.

Cost-effectiveness of policies addressing global environmental change and health

- Investigate health-related economic effects of climate change mitigation and adaptation policies (HERA)
- Cost-benefit analysis of policies to reduce global environmental change [taking into account the health impacts] (expert input)

B42. RESEARCH THEME: HEALTH IMPACT OF INTEGRAL STRATEGIES

KNOWLEDGE GAP B421.

Health effects of circular economy strategies

- Identification of safe limits for recycling and safe reuse of products potentially containing toxic chemicals (HERA)
- Assess health risks of circular economy (expert input)

KNOWLEDGE GAP B422.

Health effects of integral strategies to address global environmental change

- Assess the contribution and impact of various environmental policies set by the European Commission (i.e. strategy and action plans related to the Green Deal) on global pollution and thus on health (HERA)
- Full characterisation of how policies to protect planetary health can cause a range of changes in the state of natural systems and can affect a range of critically important dimensions of human health in the long term…[including identification of] unintended adverse results… environment and human health co-benefits can justify integrated approaches to policy solutions across disciplines and sectors) (Lancet)

B43. RESEARCH THEME: HEALTH IMPACT OF TRANSFORMATIVE CHANGES

KNOWLEDGE GAP B431.

Health effect of transformative changes to the economy to address global environmental change

- Exploration of new economic models (circular, green, wellbeing, doughnut etc.) [and their health impacts] (expert input)
- There is a growing group of economic scientists who claim that a fundamental change of the economic system is required in order to bring humanity in balance with its environment. The health effects of such a fundamental change of economic system are completely unexplored (expert input).

KNOWLEDGE GAP B432.

Health effects of transformative societal changes to address global environmental change

- The effect of multiple transitions (energy, diet, health care, ...) on human health (expert input)

B5. SUBAREA: ANALYSING ETHICAL ISSUES RELATED TO POLICIES ADDRESSING GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

B51. RESEARCH THEME: POLICIES AND 'INTRA-SPECIES' ETHICAL ISSUES

KNOWLEDGE GAP B511.

Ethical reflection on policies addressing global environmental change and human health

- What ethical principles should guide the choice of specific climate change policy objectives, including but not limited to, maximum human-induced warming and atmospheric greenhouse gas targets? (Rock)
- [On what ethical principles should economic analyses of climate change policies, such as cost-benefit analyses, be based?] (Rock, reformulated)

KNOWLEDGE GAP B512.

Ethical reflection on the distribution of responsibility for policies addressing global environmental change and human health

- Who is ethically responsible for the [health] consequences of climate change, that is, who is liable for the burdens of [adaptation] or paying for unavoided damages (Rock)
- A 'just transition' sits at the heart of planetary health, and there are questions about what this means in every domain (expert input)

B52. RESEARCH THEME: POLICIES AND 'INTER-SPECIES' ETHICAL ISSUES

KNOWLEDGE GAP B521.

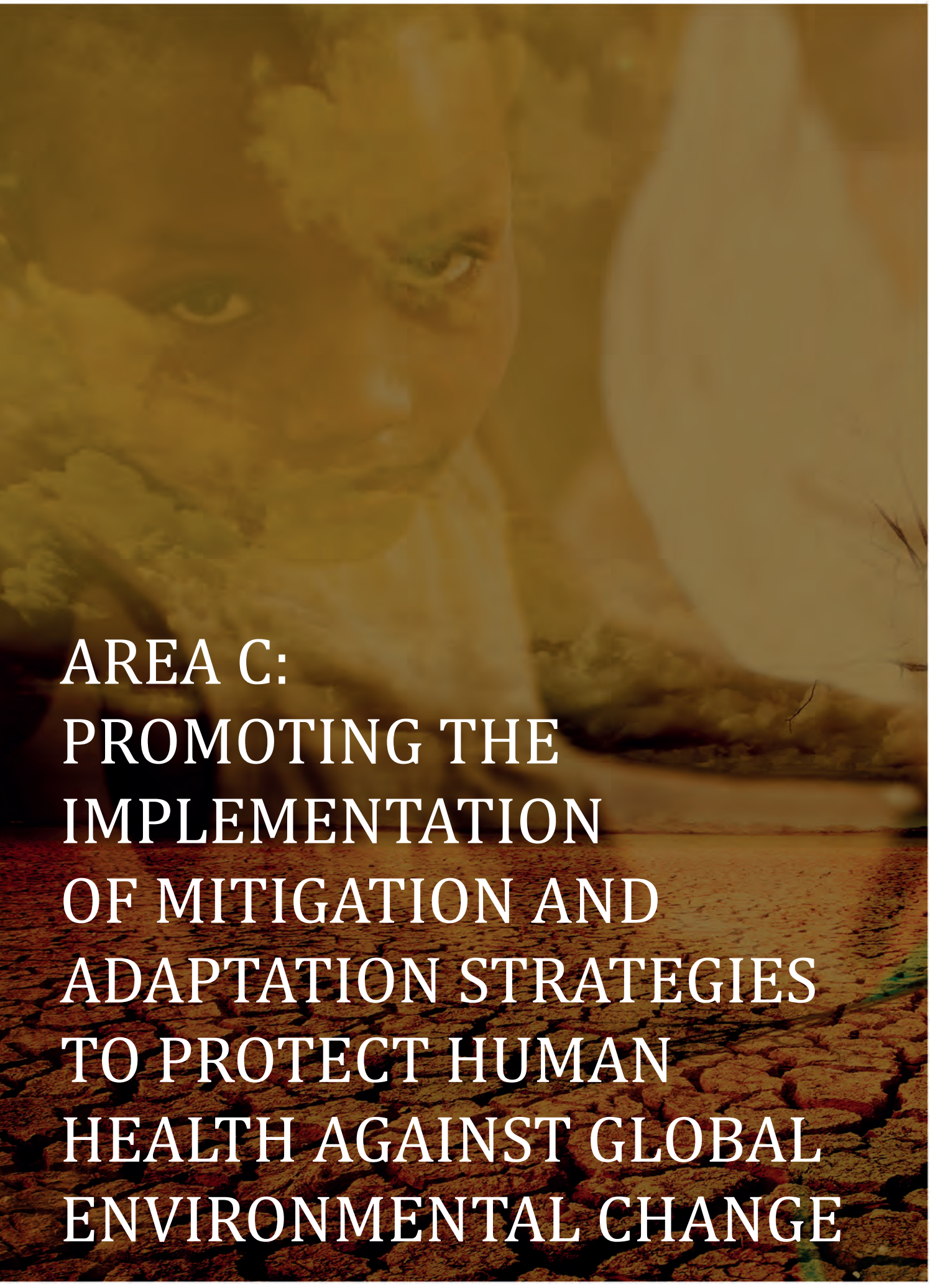
Ethical reflection on the impact of policies on the health of other species

- Ethical principles in relation to the effect/impact of policies on animals and ecosystems (expert input)
- The ethical implications of our moral responsibilities towards animals and ecosystems (expert input)

KNOWLEDGE GAP B522.

Ethical framework for planetary health, including the interests of other species

- Develop a new more holistic conceptual framing which defines a culture of ethical sustainability, including equality and vulnerable population groups and which shifts social institutions, societal norms and governance systems towards a deeper ecological philosophy (HERA)
- Develop an ethical framework [for planetary health] which has an eye for the interests of animals and nature in addition to those of humans (Meijboom)



AREA C: PROMOTING THE IMPLEMENTATION OF MITIGATION AND ADAPTATION STRATEGIES TO PROTECT HUMAN HEALTH AGAINST GLOBAL ENVIRONMENTAL CHANGE

C1. SUBAREA: DEVELOPING EFFECTIVE STRATEGIES FOR CHANGING BEHAVIOUR RELATED TO GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

C11. RESEARCH THEME: CHANGING CITIZEN BEHAVIOUR

KNOWLEDGE GAP C111.

Determinants of citizen behaviour related to global environmental changes and health

- We need to identify which cognitive, motivational, social, cultural, physical, and institutional factors influence the adoption of different sustainable innovations and technologies by individuals, households, and organisations (Steg)
- More research is needed into biases that may inhibit adequate judgements and optimal decisions related to energy behaviour of various actors (Steg)

KNOWLEDGE GAP C112.

Improving citizen understanding of the health impacts of global environmental change

- Investigating the most relevant tools and (participatory) approaches for a balanced education of citizens in the environment and health field (HERA)
- What are effective methods for informing citizens about risks and encouraging measures and prevention (sun-safe behaviours, different consumption patterns)? How can this be better linked to existing processes? Which ICT technologies can be used to reach target groups? (ZonMW)

KNOWLEDGE GAP C113.

Contextual approaches to changing citizen behaviour related to global environmental change and health

- The identification of effective economic (including changing behavioural incentives)... approaches to promote planetary health...; develop and implement appropriate taxes and subsidies that promote sustainability, improve health, and reduce inequities...; support local sustainable development initiatives; and regulate harmful activities (Lancet)
- We need to better understand the psychological and behavioural effects of contextual changes that aim to make sustainable energy behaviour more attractive or feasible (Steg)

KNOWLEDGE GAP C114.

Inequalities in citizen behaviour related to the health impact of global environmental change

- What are success and failure factors [of climate adaptation measures] (especially in relation to behaviour) and how is this distributed among the different population groups? (ZonMw)
- Which actors, communities, and stakeholders have been excluded from participation in environmental and human health research and decision-making, and how can these barriers be overcome? (NSF)

C12. RESEARCH THEME: CHANGING POLICYMAKERS' BEHAVIOUR

KNOWLEDGE GAP C121.

Determinants of institutional and policymakers' behaviour related to global environmental change and health

- We [also] need a better understanding of factors influencing sustainable energy use...of organisations, firms, industry and governments (Steg)
- [A] better understanding of factors influencing (un) sustainable energy behaviour in developing and emerging countries is critical (Steg)

KNOWLEDGE GAP C122.

Understanding barriers to implementing policies addressing the health impacts of global environmental change

- [D]efining approaches and tools for translating and implementing scientific evidence into policies and profound societal and behavioural transformational change processes and technological innovations supporting sustainability and green transition on national and local level, taking benefit of living labs, testbeds or other relevant approaches and platforms (HERA)
- To analyse causes of the poor translation of recommendations into policy and action. How can research better capture the barriers to policy and behaviour change? (Lancet)

KNOWLEDGE GAP C123.

Improving policymakers' understanding of the health impacts of global environmental change

- Evaluate the effectiveness of knowledge translation of innovative methods and approaches to reduce harmful exposures in urban environments (HERA)
- There is a need to investigate especially the science-to-policy interface to improve the translation of research results into policy. Research is also needed on how to best include stakeholder communication and input in a broader risk governance framework (HERA)

KNOWLEDGE GAP C124.

Harnessing public support for policies related to global environmental change and health

- It is crucial to better understand which factors affect support for energy policies, energy system changes, energy infrastructure and innovations, and how to address public concerns so that broader positive societal outcomes can be achieved (Steg)
- [L]ittle is known about which factors affect perceived legitimacy and fairness of policies and how this in turn affects the support for energy policies and system changes (Steg)

C13. RESEARCH THEME: CHANGING HEALTH CARE PROFESSIONALS' BEHAVIOUR

KNOWLEDGE GAP C131.

Determinants of health care professionals' behaviour related to global environmental change

- We need to identify which cognitive, motivational, social, cultural, physical, and institutional factors influence the adoption of environmentally sustainable health care practices (expert input)
- [Understand environmentally relevant] decisions in health care, most of which are taken by autonomous health professionals, not by citizens, managers, or policymakers. For instance, they tend to prioritise (individual) patient safety over everything else (expert input)

KNOWLEDGE GAP C132.

Understanding barriers to implementing health care policies related to global environmental change

- Conducting research focused on supporting implementation, for example, understanding the barriers to change or assessing the co-benefits of sustainable approaches (WHO)
- The challenge remains how to weigh (individual) patient benefits against climate impacts and how to communicate that to the public (expert input)

KNOWLEDGE GAP C133.

Promoting implementation of sustainable health care practices

- [R]esearch on effective ways leading to better incorporation of environmental health and health prevention as an integral part of the healthcare ecosystem (HERA)
- Embedding environmental sustainability in wider health research, with environmental costs and benefits treated as an outcome measure or a dimension of quality akin to access or equity (WHO)

C2. SUBAREA: DEVELOPING EFFECTIVE GOVERNANCE FOR IMPLEMENTATION OF MITIGATION AND ADAPTATION STRATEGIES

C21. RESEARCH THEME: LEGAL INSTRUMENTS TO ADDRESS GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

KNOWLEDGE GAP C211.

Effective national laws to address global environmental changes and health

- Largely absent from the past decade of [climate] adaptation law reform is evaluation of effectiveness (Jefferson)
- The design of [climate adaptation] laws must (1) be responsive to change; (2) address equity dimensions of climate change; (3) implement innovative solutions; (4) maximize co-benefits; and (5) establish processes for managing trade-offs (Jefferson)

KNOWLEDGE GAP C212.

Effective international laws to address global environmental changes and health

- [Develop] textual and operational reforms [to increase the effectiveness of WHOs] International Health Regulations (Gostin)
- Higher standards and more effective compliance are necessary for international law [i.e., trade law, food security law, environmental law, humanitarian law, and refugee law] to realize its full potential to safeguard the world's population (Garcia)

KNOWLEDGE GAP C213.

Effectiveness of litigation in addressing global environmental changes and health

- [There is] very little evidence of the extent to which the growing number of [climate change litigation] cases...are either driving action to address climate change or creating awareness of the issue (Setzer)
- Another aspect to consider is the potentially negative impacts that can result from [climate change litigation] lawsuits (Setzer)

C22. RESEARCH THEME: GOVERNANCE STRUCTURES AND PRACTICES TO ADDRESS GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

KNOWLEDGE GAP C221.

Effective local governance to address global environmental change and health

- How can climate and health policies be best organized at the local/regional level? What are effective governance processes in this context? Where does the responsibility lie for vulnerable groups, for example? (ZonMW)
- There is a need to develop knowledge to understand the operational pathways and institutional structures for governance that effectively supports climate action in different urban contexts (IPCC 2)

KNOWLEDGE GAP C222.

Effective national governance to address global environmental change and health

- The identification of effective... governance approaches to promote planetary health, including how best to reduce and recycle harmful subsidies; develop and implement appropriate taxes and subsidies that promote sustainability, improve health, and reduce inequities; support local sustainable development initiatives; and regulate harmful activities. (Lancet)
- [Develop] good resource management practices for soil and water that contribute to promoting sustainable food systems, with payments for ecosystem services as an option (UN)

KNOWLEDGE GAP C223.

Effective international governance to address global environmental change and health

- In terms of governance, a global management system for water is needed, specifically a negotiation system, as well as a global water strategy (JPI)
- Strengthen [Common Agricultural Policy] related governance research in order to better integrate environment, biodiversity, climate change and health issues into agriculture policy and the related food systems (HERA)

C3. SUBAREA: ENABLING TRANSFORMATIVE CHANGE TO COUNTER GLOBAL ENVIRONMENTAL CHANGE AND PROTECT HEALTH

C31. RESEARCH THEME: DISCOVERING MECHANISMS FOR TRANSFORMATIVE CHANGE

KNOWLEDGE GAP C311.

Mechanisms for transformative change (general)

- Study the underlying, direct and indirect drivers of transformational change in behaviour, policy, economy, and technology to reveal leverage points to bring about the conservation, restoration and sustainable use of biodiversity, while taking into account human and planetary health (HERA)
- We call on both social and natural sciences to engage more intensively in collaborative interdisciplinary research to understand rapid social transformations, social tipping elements, and their interactions (Otto)

KNOWLEDGE GAP C312.

Historical precedents for transformative change

- [Use historical analysis] to increase understanding about the constraints of, and opportunities for, long-term change processes (Kanger)
- Historical analysis of path dependencies that need to be overcome to realise transformational change (expert input)

C32. RESEARCH THEME: DEVELOPING METHODS FOR TRANSFORMATIVE CHANGE

KNOWLEDGE GAP C321.

Methods to promote transformative change (general)

- A key area is the interactions between enabling conditions such as finance, behaviour, and innovation and how they can accelerate transitions (expert input)
- Developing effective methods for citizen engagement (expert input)

KNOWLEDGE GAP C322.

Methods to promote transformative change of specific subsystems

- [E]mpirical and modelling efforts to better understand the potentials of harnessing social tipping dynamics for climate change mitigation (Otto)
- Develop, redesign and apply research on the food system transformation in order to provide healthy nutrition for European urban and rural populations while staying within planetary boundaries and also safeguarding natural capital for the future (HERA)

AREA D: ENABLING RESEARCH ON GLOBAL ENVIRONMENTAL CHANGE AND HEALTH

D1. SUBAREA: IMPROVING DATA AND METHODS FOR RESEARCHING AND MONITORING GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

D11. RESEARCH THEME: DATA INFRASTRUCTURE

KNOWLEDGE GAP D111.

Climate change and health information systems

- Develop health and climate-related information systems to guide the development of adaptation measures and provide scientific evidence (HERA)
- Develop innovative health climate-related services including an integrated early warning system (HERA)

KNOWLEDGE GAP D112.

Biodiversity and health information systems

- Implement longitudinal research, which builds on existing and novel data sets and registers, measuring tools and artificial intelligence to better characterise, monitor and model biodiversity and health related pathways and related indicators to improve monitoring (HERA)

KNOWLEDGE GAP D113.

Pollution and health information systems

- Developments in digital health and large-scale as well as dedicated cohort studies are needed to monitor immediate to long-term impacts of air pollutants as well as their mixture (HERA)
- Innovative approaches are needed to ensure linkage and interoperability of different data sources (e.g. air pollution and waste water monitoring systems, disease registries) and access to information updated in real time, coupled with HIA and modelling platforms (HERA)

KNOWLEDGE GAP D114.

Sustainable and healthy diet information systems

- Data platform for modelling healthy and sustainable dietary patterns (WHO)
- Set up a monitoring system to assess the status of food environments, and to measure progress on achieving the goals of nutrition and health plans (Food-EPI)

KNOWLEDGE GAP D115.

Infectious disease information systems

- Implement ecological health observatories in hot spots of disease emergence (HERA)
- Effective surveillance for known and potential zoonoses (and diseases that threaten livestock and wildlife) in the wildlife trade is crucial (IPBES)

KNOWLEDGE GAP D116.

Integrated planetary health information systems

- Many information systems already exist. What is missing is the ability to integrate information from different systems (expert input)
- Simultaneously monitoring population and planetary health is critical for understanding the causal pathways between environmental parameters (including weather/climate, atmosphere, land use and crop yields, biodiversity) and the health and well-being of populations, taking into account the multiple drivers of adverse health outcomes (Ebi)

D12. RESEARCH THEME: MEASUREMENT METHODS

KNOWLEDGE GAP D121.

Measurement of exposure to biodiversity

- Novel methods are needed to accurately quantify...exposures to different dimensions of biodiversity (Aerts)
- Quantitative indicators defining the relationships between biodiversity and human and planetary health/well-being to inform and support transformational change pathways in economy, policy and planning are not sufficiently developed (HERA)

KNOWLEDGE GAP D122.

Measurement of exposure to global pollution

- Novel approaches in monitoring technologies, techniques and reporting of air quality are needed for an assessment of the new WHO guideline implementation. In addition, also novel approaches for the monitoring of ultrafine particulate air pollution is needed e.g. of desert dust in PM (HERA)
- Linking human biomonitoring of exposure and effect biomarkers to citizen-science by making sampling easier, cheaper, less invasive (HERA)

KNOWLEDGE GAP D123.

Measurement of early health effect markers of global environmental change

- Develop advanced approaches for incorporation of early effect markers in the environmental burden of disease assessments (HERA)

D13. RESEARCH THEME: ANALYTIC METHODS

KNOWLEDGE GAP D131.

Attribution of health effects to global environmental change

- A very recent scientific development is the possibility of attributing specific extreme weather events to climate change. As a follow-up to that, one may explore the possibility of attributing certain health effects to a specific type of extreme weather event (expert input)
- Improve methods for attribution of health effects to climate change, with special attention for combined exposures of environmental stressors (exposome: temperature, air pollution, pollen etc.) and linkage between environmental, socio-economic and health data (HERA)

KNOWLEDGE GAP D132.

Health systems' contribution to global environmental change

- Developing standard metrics and research methods for assessing the environmental costs and benefits of health system activities (WHO)

KNOWLEDGE GAP D133.

Complex interactions between exposures

- Development of analytical tools that are able to handle high levels of complexity, e.g. interactions and feedback loops between climate change, biodiversity loss, and global pollution, and how these affect human health (expert input)
- Development of new methods, such as the 'exposome', to identify interrelationships between global environmental change entities that relate to human health (expert input)

KNOWLEDGE GAP D134.

Integration of evidence on the health effects of global environmental change

- Development of methodologies that take stock of multiple lines of evidence coupling epidemiological evidence from human cohort studies and toxicological data (HERA)
- Develop a unified EU approach on quality of life and burden of disease related to climate change measures (HERA)

KNOWLEDGE GAP D135.

Trade-offs between the short-term and long-term health effects of policies addressing global environmental change

- The assessment of trade-offs between short-term gains and longer-term benefits can support transparent decision making. (Lancet)
- How can current and future effects be mapped in a comparable manner? (ZonMw)

KNOWLEDGE GAP D136.

Economic valuation of the health effects of global environmental change

- [W]e still know little about the marginal value of biodiversity (i.e. value associated with changes in the variation of genes, species, and functional traits) in the production of [ecosystem] services (Cardinale)
- [E]fforts must be made to embrace the true value of food. External costs associated with climate change, biodiversity loss, and adverse health effects need to be considered (UN)

KNOWLEDGE GAP D137.

Integral health impact assessment of policies addressing global environmental change

- Develop and apply methods to evaluate and monitor the (cumulative) health impacts of mitigation and adaptation measures in an integrated and harmonized way within or across sectoral policies (HERA)
- Development of quantitative impact assessment of air and water quality guidelines and global flow of materials and goods regulations (HERA)

D14. RESEARCH THEME: QUANTITATIVE MODELS

KNOWLEDGE GAP D141.

Models forecasting the health effects of climate change and climate-related policies

- Develop integrated forecast models and tools for health impacts of climate change, including epidemiological models and socio-economic trajectories of exposure and vulnerability (HERA)
- [Forecasting the health effects of climate change and climate-related policies] demands the explicit incorporation of projections of future demographics and population health parameters (expert input)

KNOWLEDGE GAP D142.

Models forecasting health effects of biodiversity loss and biodiversity-related policies

- We also need sets of models and statistical tools that help us move from experiments that detail local biological processes to landscape-scale patterns where management and policy take place (Cardinale)
- Ideally, predictions arising from landscape-level models would be 'ground-truthed' by assessing their ability to predict the outcome of real restoration projects, or other management scenarios where policy actions are being taken to protect ecosystem services (Cardinale)

KNOWLEDGE GAP D143.

Models forecasting the health effects of global pollution and pollution-related policies

- Further development of exposure modelling linking sources to internal exposure ultimately leading to improved prediction of body burden based on environmental data (HERA)
- Development of harmonised approaches for modelling frameworks relevant for human health risk assessment,development of a harmonised protocol for models that should be used in a regulatory context (HERA)

KNOWLEDGE GAP D144.

Models forecasting the food-mediated health effects of global environmental changes and related policies

- The same ambitious methods used in the past decade to model future climates and agricultural impacts must be matched by modelling the economics of diets, and the multidirectional relationships among diet, human health and planetary boundaries (GlobPan)

KNOWLEDGE GAP D145.

Models forecasting infectious diseases related to global environmental changes and related policies

- The modelling of disease risks and pathogen evolution to adapt prevention and mitigation strategies and anticipate the evolutionary potential of pathogens that may threaten treatment and vaccination strategies (HERA)
- Many of the modeling efforts that explore the links between environmental change and infectious disease are still theoretical...In order to advance predictive modeling, there is a need for linked, long-term data at multiple spatial and temporal scales to support assessments of functionality within and across ecological and human behavioral systems, and over time (NSF)

KNOWLEDGE GAP D146.

Integrated models forecasting the health effects of global environmental change and related policies

- Studies focused on understanding, assessing, and responding to multiple hazards have been limited, ...predominantly focused on two hazards rather than the complex multitude of stressors that simultaneously affect socioenvironmental systems. [We need new models] for exploring overlapping stressors spatially through simulation of future scenarios (NSF)
- Various modelling approaches, e.g. spatially explicit land-use models and ecosystem services models, [must be] integrated in a single framework of analysis to identify possible side-effects and synergies emerging from policy implementation (Pongisir)

D2. SUBAREA: CREATING CONDITIONS CONDUCIVE TO RESEARCH ON GLOBAL ENVIRONMENTAL CHANGES AND HEALTH

D21. RESEARCH THEME: RESEARCH PRACTICES

KNOWLEDGE GAP D211.

More interdisciplinary and transdisciplinary research

- [U]niversities and research institutes need to find new ways to encourage transdisciplinary research teams to investigate scientific questions of societal importance and to develop, reward, and promote academic staff pursuing a research agenda informed by the planetary health framework (Lancet)
- Strengthening the interactions among scientists specializing in food systems, health, climate, and energy will make it possible to generate the required expertise (UN)

KNOWLEDGE GAP D212.

More science-policy dialogue

- Improve dialogue and understanding between science, stakeholders and policy by effective and comprehensive communication of results and solutions as well as risks and uncertainty to various audiences across disciplines and stakeholder types to foster trustworthiness, counter misinformation and build capacities and skills (HERA)
- [M]ore [food-related] research needs to be driven by the specific needs of policy makers (GlobPan)

KNOWLEDGE GAP D213.

More participatory research

- Innovative, interdisciplinary, people-centered, participatory research to foster crucial trust and transform people's perception of risk and their risk-reduction behaviors and communicate prevention (Ebi)
- Utilise participatory research with under-represented groups to address societal needs through citizen science where the public contributes to data gathering to monitor local environments, in order to address environmental injustice where there is disproportionate exposure of certain populations to environmental hazards (HERA)

KNOWLEDGE GAP D214.

More implementation research

- [P]rioritise translational research and implementation science to address the on-the-ground realities of what is feasible and relevant in the settings facing the greatest threats (Lancet)
- Rigorous implementation research is needed to strengthen the fit-to-context design delivery of [food systems] programs (UN)

KNOWLEDGE GAP D215.

More evidence synthesis

- [N]eed for capacity strengthening to develop a global collaborative effort analogous to the Cochrane Collaboration, which oversees the co-ordination of systematic reviews that link health and environmental sustainability (Lancet)
- Establish inter-governmental and global institutional mechanisms to better forge credible and authoritative consensuses on scientific evidence, resolving controversies surrounding new [food systems-related] research (GlobPan)

D22. RESEARCH THEME: TRAINING OF SCIENTISTS AND PRACTITIONERS

KNOWLEDGE GAP D221.

More educational content related to global environmental change and health

- Advanced educational programs at all levels (research scientists, professionals, citizens) combining the science areas relevant for addressing environment, climate and health, promoting trans-disciplinary science and holistic perspectives (HERA)
- What knowledge does practice (care, health services, construction, various governments) need? How can this be integrated into existing curricula? (ZonMw)

KNOWLEDGE GAP D222.

More interdisciplinary and transdisciplinary education

- Beyond the challenge of building complex, interdisciplinary research teams, there are structural challenges to performing such work. One such challenge, at the university level, is that training of young scientists tends to be focused within disciplines and there are few incentives for scientists to work across health and environmental disciplines (NSF)
- We need to encourage trans-disciplinary science education and develop advanced educational programs at the undergraduate and graduate levels bridging and connecting several domains together (chemistry, biology, physics, public health, statistics, informatics etc.) in order to address environmental health challenges (HERA)

Literature

Abbreviation used in Knowledge gaps	Complete Reference
Aerts	Aerts R et al. (2018) *Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces.* British Medical Bulletin 2018;127:5–22. https://academic.oup.com/bmb/article/127/1/5/5051732 .
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Coffey	Coffey Y et al. (2021). *Understanding Eco-anxiety: A Systematic Scoping Review of Current Literature and Identified Knowledge Gaps.* The Journal of Climate Change and Health 2021; 3, 100047 https://doi.org/10.1016/j.joclim.2021.100047 .
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Glob Pan	Global Panel on Agriculture and Food Systems for Nutrition (2020). *Future Food Systems: For people, our planet, and prosperity.* London, UK. https://foresight.glopan.org/
Gostin	Gostin, L.O. and Katz, R. (2016). *The International Health Regulations: The Governing Framework for Global Health Security.* Milbank Q. 2016 Jun; 94(2): 264–313. https://dx.doi.org/10.1111%2F1468-0009.12186
HERA	HERA Consortium. *EU Research Agenda for the Environment, Climate and Health* 2021-2030.Final draft (2021). www.heraresearcheu.eu
IPBES	IPBES (2018): *The IPBES assessment report on land degradation and restoration.* Montanarella, L., Scholes, R., and Brainich, A. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. https://doi.org/10.5281/zenodo.3237393
IPBES2	IPBES (2019): *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.3831673.

Abbreviation used in Knowledge gaps	Complete Reference
IPCC1.5	Ebi, K. et al (2018). *IPCC The 1.5 Health Report*, https://ghhin.org/resource-library/
IPCC2	Prieur-Richard, A.H. et al.(2018). *IPCC Extended version: Global Research and Action Agenda on Cities and Climate Change Science.* https://www.ipcc.ch/site/assets/uploads/2019/07/Research-Agenda-Aug-10_Final_Long-version.pdf.
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Lilford	Lilford R et al. (2016) *The health of people who live in slums 2.* The Lancet 2016; 10068. https://DOI:10.1016/S0140-6736(16)31848-7.
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NCOH	NCOH research themes infographic and Strategic research agenda 2021. Research Themes - NCOH. https://ncoh.nl/research/research-themes
NSF	*Environmental and Human Health: Research Priorities* (2021), National Science Foundation, The public health and environmental research and education subcommittee
Otto	Otto IM et al. (2020). *Social tipping dynamics for stabilizing Earth's climate by 2050*. Proc Natl Acad Sci U S A, 2020; 117(5):2354-2365. https://doi.org/10.1073/pnas.1900577117
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Rock	Brown, D. et al (2013). *White paper on the ethical dimensions of climate change.* Widener Law School Legal Studies Research Paper No. 13-58. https://ssrn.com/abstract=2304401
SAPEA	A Scientific Perspective on Microplastics in Nature and Society (2019). Science advice for policy by European Academies (SAPEA). ISBN 978-3-9820301-7-3. https://doi.org/10.26356/microplastics
Setty	Setty K et al. (2019). *Faster and Safer: Research Priorities in Water and Health.* Int J Hyg Environ Health 2019; 222(4): 593–606. doi: https://doi.org/10.1016/j.ijheh.2019.03.003.
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KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

APPENDIX 3
EXPERTS INVOLVED IN THE CONSULTATION PROCEDURES

(1): Experts involved in compiling the longlist of knowledge gaps
(2): Experts involved in the priority-setting exercise
(3): Experts involved in developing recommendations for implementing the research agenda or commenting generally on the report.

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APPENDIX 4
REVIEW OF THE REPORT

At the request of the Academy's Board, a draft of this report was reviewed by the following individuals:

- Kristi Ebi, Professor of Global Health and Environmental and Occupational Health Sciences, University of Washington
- Maarten Hajer, Professor of Urban Futures, Utrecht University
- Roel Vermeulen, Professor of Environmental Epidemiology and Exposome Science, Utrecht University
- Marcel Verweij, Professor of Philosophy, Wageningen University & Research
- Maria Yazdanbakhsh, Professor in Cellular Immunology of Parasitic Infections, Leiden University Medical Center

In addition, the report was reviewed by:

- The Academy's Council for the Humanities
- The Academy's Council for Medical Sciences
- The Academy's Council for Natural Sciences and Engineering
- The Academy's Social Sciences Council

The reviewers are not responsible for the final report.