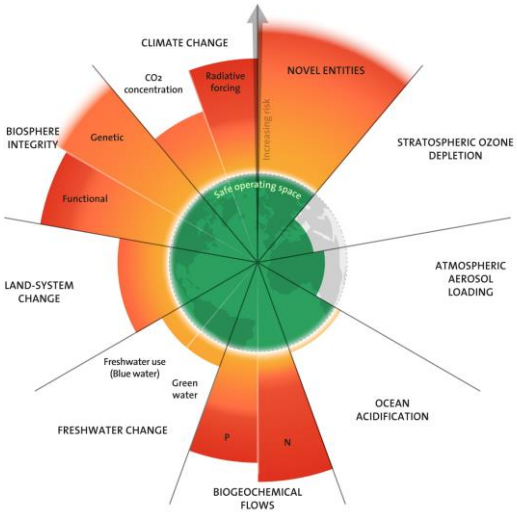
The CLIMAR Network examines the relationship between AMR, climate change, pollution, biodiversity, and other drivers that have been captured by the Stockholm Resilience Centre's 'planetary boundaries' concept. This concept connects nature, health, equity and social justice, recognising their complexity within interconnected systems and, through social and organisational mobilisation movement building, ensures a systems change covering human, animal and environmental health. The aim of the network is to find transdisciplinary solutions that will reduce and prevent AMR infections whilst promoting innovations for alternative interventions. Ten Working Groups, each focusing on a particular planetary boundary or planetary health thread, will be instrumental in this.



Working Groups: Planetary Boundaries *Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023 .*

There are nine Planetary Boundaries. Three – Climate Change, Novel Entities and Biosphere Integrity – align with the Triple Planetary Crisis issues of climate change, pollution and biodiversity loss. The Working Groups will focus on five boundaries, which are the most relevant to help understand and explain the linkages between AMR and Climate Change: **Biosphere Integrity, Novel Entities, Freshwater Change, Land-System Change,** and **Biogeochemical Flows.**

(As for the remaining boundaries, three - Ocean Acidification, Ozone Depletion and Atmosphere Aerosol Loading – are not focused on, as there is limited evidence that these are associated with AMR - though the network will critique this position - while the intersection of the ninth, climate change, permeates all the working group focus areas.)

Working Groups: Planetary Health Threads

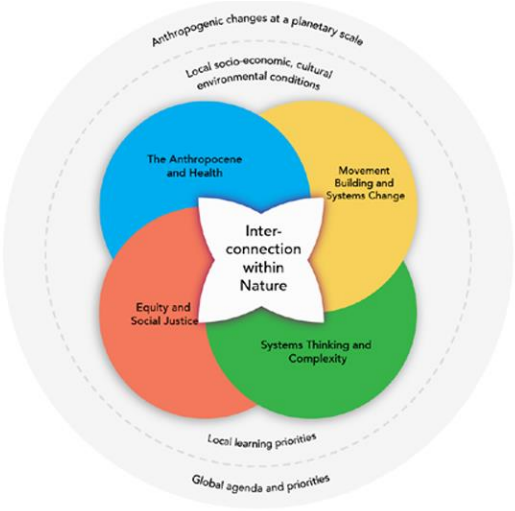


Figure 3. The Planetary Health Education Framework.

*Guzman et al. (2021), Planetary Health Education Framework***.**

Based on the PHA's Education Framework, there are five Planetary Health domains, all of which all intertwine and interact as a single thread. All of these are the focus of Working Groups**: Interconnection within Nature, The Anthropocene and Health, Equity and Social Justice, Systems Thinking and Complexity,** and **Movement Building and Systems Change**.

Please see the Working Group Terms of Reference for more information about how the Working Groups will share findings and intersect.

Working Group aims and outputs

To review current understandings of AMR in the context of the working group focus. Suggested outputs:

a. A two-page policy brief on AMR and the Working Group focus
b. Stakeholder mapping, to aid with movement building and systems change
c. Suggestions for key gaps in current research
d. Planning activity for the Working Group across CLIMAR's project lifetime.

Questions to consider

- Who are the stakeholders we need to communicate with?
- Who might be missing from the conversation?
- Where are the research gaps?
- Where are the methodological gaps (surveillance systems, policies etc)?
- What co-benefits are there, to whom, if AMR is tackled effectively in this area?
- What are the challenges, and who/what presents them, to acting on recommendations and taking advantage of available benefits?
- Do the benefits to one working group focus present challenges to others that require considerations of compromise or deconfliction?
- What are the key messages we need to convey to policymakers – and which policymakers?
- Are there any opportunities that can be exploited?
- What are the challenges we need to be mindful of?
- Can we identify and employ a common conceptual 'language' via which to work across disciplines in a truly ('lived') transdisciplinarity?

Quick Links:

[Biosphere Integrity]

[Novel Entities]

[Freshwater Change]

[Land System Changes]

[Biogeochemical Flows]

[Interconnection Within Nature]

[The Anthropocene and Health]

[Systems Thinking and Complexity]

[Equity and Social Justice]

[Movement Building and Systems Change]

[Other key reading]

Biosphere Integrity

The Triple Planetary Crisis refers to three primary interlinked issues that humanity currently faces: climate change, pollution and biodiversity loss [1] [2]. These challenges are included within the Planetary Boundaries framework. Biodiversity encompasses microbial diversity, that which both underpins ecosystem function and includes microorganisms that produce the antibiotics harnessed to treat infection. Microbial biodiversity also includes reservoirs of antibiotic resistance mechanisms that are continually emerging in human pathogens. Direct climate change impacts will be largely felt by environmental microbiomes, with direct effects of temperature, precipitation, UV exposure, salinity and pH and indirect effects of CC including human population perturbations, changes in wild animal migration patterns, animal trade routes and agricultural practice etc [3][4]. It's therefore critical to understand the intersection of human induced climate change, pollution and changes in biodiversity within the context of the AMR pandemic.

AMR is not a simple phenomenon. Resistance can be acquired through mutation, many of which occur in pathogens during antibiotic chemotherapy in humans and/or animals and potentially in antibiotic polluted environments. However, much resistance occurs through acquisition of antimicrobial resistance genes through horizontal gene transfer. Current understanding concludes that the majority of these genes have origins in nature predating antibiotic use, the existence of humans and perhaps, for some, even the existence of multicellular life. To some it might seem surprising that resistance predates use of antibiotics, but we need to emphasise that most of our antibiotics are products that are produced naturally by bacteria and fungi and resistance to these antibiotics has evolved over evolutionary time. Therefore, this critical component of the AMR pandemic is rooted in microbial biodiversity. Climate change, environmental pollution and other anthropogenic outcomes effect microbial diversity in the same way that human activity impacts plant and animal biodiversity [5].

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Novel Entities

Novel entities are defined in the Planetary Boundaries model as "synthetic chemicals and substances (e.g., microplastics, endocrine disruptors [...] anthropogenically mobilized radioactive materials)" [1]; i.e. substances that would not exist in Earth systems without human intervention. The model also considers novel entities to be those that arise due to "human modification of evolution, genetically modified organisms and other direct human interventions in evolutionary processes". The impacts of these novel entities on Earth systems are understudied, including their interaction with the other planetary boundaries. The need to understand the type and quantity of novel entities the Earth system can safely tolerate is especially pertinent to AMR; where a lack of knowledge transgresses a key planetary health ethic the "right to know the risk" [2]. Antibiotics themselves can be novel entities, as too can their alternatives such as bacteriocins etc. Synthetic chemicals such as biocides and detergents [3], and heavy metals [4] can drive evolution and the emergence of resistance. The use of novel antimicrobials can have unintended consequences, such as the negative impact of early antibiotic exposure on various childhood conditions [5, 6] or the disposal of human waste containing antibiotic residues mixing with other pollutants in watercourses forcing the evolution of resistance [7]; the latter shows seasonal variations in the abundance and diversity of ARGs detected, which may be exacerbated by climate change.

Environmental progenitor genes that can transfer to pathogens and evolve to form related groups of resistance gene variants with a clinical signature can also be considered novel biological entities [8]. These novel genes are prevalent in polluted environments, including in environmental bacterial strains, suggesting that bidirectional transmission and gene transfer events are common between human and environmental microbiomes [9].

Skewing microbiomes towards predominately resistant organisms reduces the safe operating space for AMU, necessitating increased use and development of further novel entities (antimicrobials). The use of novel entities is not always well regulated, compounding the challenge. The use and release of chemicals without adequate safety assessment (including the cocktail effects of chemical mixtures under different conditions), thus presents a key challenge to AMR and climate change, yet more than ~80% of chemicals registered in the EU are in use for ~10 years before undergoing safety assessment [10] and safety assessments that do occur rarely consider potential Earth system effects. We know that novel entities such as antimicrobials have accelerated AMR evolution. How climate change will affect AMU across all sectors requires further, systemwide study.

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Freshwater Change

Freshwater change is one of nine planetary boundaries and includes both blue water (e.g., rivers and lakes) and green water (e.g., soil moisture). Natural functions such as carbon sequestration and biodiversity that rely on freshwater cycles, can be altered by human disturbances to water [1]. Antimicrobials, antimicrobial resistant bacteria (ARBs), and antimicrobial resistant genes (ARGs) are continuously received by freshwater bodies (such as rivers and lakes) from processes such as agriculture, aquaculture, healthcare, manufacturing activity and wastewater; meaning freshwater change is strongly associated with AMR evolution and transmission, contributing to reservoirs of AMR within the environment [2].

Current AMR thinking prioritises water, sanitation and hygiene (WaSH) although action to improve WaSH is sometimes considered as being within other Sustainable Development Goal objectives and not specifically related to AMR. Improvements in WaSH are therefore considered as AMR sensitive interventions (those that are designed for other purposes but have co-benefits in terms of reducing AMR evolution and/or transmission, as opposed to AMR specific interventions that are primarily designed to impact AMR). In reality the role of freshwater systems in relation to AMR reaches far beyond WaSH, and the combined impacts of multiple drivers, including climate change and processes associated with other planetary boundaries, are important to consider.

AMR and freshwater systems remain an area of research gaps. Models need to be developed to estimate the potential impacts of freshwater change on AMR and indeed how climate change scenarios may impact these. Additionally, the development of metrics and indicators for the tracking of AMR in freshwater systems under climate change will be imperative for assessing the future risks to public health.

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Land-System Change

While not exceeded to such an extent as some of the other planetary boundaries, Land-System Change is still a domain under stress. Land-system change impacts AMR through agricultural and urban land systems in complex entanglements. Urban conurbations cover only ~2-3% of Earth's total land mass [1] but around half of Earth's habitable land is used for agriculture (growing crops and grazing livestock) to feed increasingly urban populations, making urban and rural land areas impossible to consider in isolation. There have been concerns for decades that the world will run out of land to grow food unless the human population stops increasing at the current rate (0.85% *pa*), or populations move to a considerably more plant-based diet [2]. Agricultural processes push for increased yields on comparatively less land, enabled by artificial fertilizers and livestock intensification [3] that in turn impact soil biota [4]. Globally, 40% of arable soil is considered degraded and could increase to 95% by 2050 [5].

In addition, increased urbanisation can change catchment hydrology by altering the amounts of surface runoff, as well as contributing greater amounts of human sewage. Informal urban settlements pose a particular challenge [6], while the use of strong detergents containing products including parabens, triclosan, and ammonium compounds in more affluent, developed urban regions can also drive resistance, along with a host of other factors that suggest urban environments are an overlooked AMR challenge [7]. Land-system changes in intensive farming impact AMR through high antimicrobial use to address animal ill-health caused by overcrowding and poor welfare conditions, driven by increasing meat content of urban diets. As climate change challenges crop yields, particularly in areas of the world that are under the most climate stress such as India and the Middle East, increasing numbers of farmers move from crop farming into livestock with little understanding of how to manage animal health in intensive systems, creating a vicious circle of poor health and high antibiotic use. This has been observed in poultry, dairy cattle, and aquaculture [8, 9, 10, 11].

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Biogeochemical Flows

Management of agricultural land includes application of agricultural fertilisers, manures and biosolids, associated with biogeochemical flows of nitrogen and phosphorus. Bacteria are involved in both nitrogen and phosphorus cycles and are also involved in carbon and sulphur cycling. "The synthetic production of nitrogen entering ecosystems through fertilizers is now greater than all forms of natural production combined, and phosphorus levels in bodies of water due to the runoff from agricultural and mining activities are dangerously high, though under-reported" [1]. We can think about biogeochemical flows in the context of manure and biosolids specifically, how these practices designed to enrich nitrogen and phosphorus in soils for plant growth also leads to the introduction of both exogenous bacteria from humans and animals that include pathogens and AMR mechanisms, and antimicrobial residues that have the capacity to drive further evolution of resistance [2,3]. Urban geochemical flows are also worth thinking about: cleaning products and air pollution from traffic also cause challenges, and more environmental investigation is needed.

We can also think about biogeochemical flows from a climate change perspective. We know that nitrous oxide and methane are potent greenhouse gases and that microbial activity is responsible for production of both. However, the impact of antibiotics on microbial community function is poorly understood, particularly at the concentrations found in agricultural soils [4,5]. Carbon cycling is also heavily impacted by microbial respiration, with CO_2 production being a function of bacterial metabolism. We know that respiration rates can increase with temperature, but it is unclear how antibiotic stress may impact soil and aquatic microbial communities.

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Interconnection Within Nature

Western, Judaeo-Christian traditions depict humans as having dominion over nature and thereby being *apart from* nature, whereas other (non-Western) traditions, including aboriginal or First Nations, often locate humans as an intrinsic *part of* nature. Human interaction with nature, which depicts humans as *a part of* nature, is a central perspective of the Planetary Health Framework. This eco-centric framework emphasises the need for humans to understand our role in nature as individuals and as a species, and was pre-dated by the work of the nineteenth-century British and American Conservationist and Preservationist Movements; e.g. the proto-environmentalism in the work of George Perkins Marsh – *Man and Nature* (1864) [1] – who argued that human actions were degrading the environment a century before Rachel Carson's *Silent Spring* (1962) [2] the late nineteenth-century development of ecology as a scientific field that investigated the interconnectedness of species and environments; and the ethical roots of Aldo Leopold's 'Land Ethic' (1949) [3] depicting humans as part of a broader biotic community who should preserve the integrity, stability, and beauty of the ecosystem. These eco-centric framings are in sharp contrast to the widely adopted anthropocentric logic of the United Nations Brundtland Commission's 1987 definition of *sustainability*, which is more interested in the sustainability of the environment for the benefit of future human generations, than in the sustainability of the planet for the benefit of all life, as well as for the planet itself.

The Planetary Health Framework conceptualises 'interconnection' as an indicator for 'mutualism, reciprocity, and symbiosis' [4]. These interconnections can also be understood via the concept of *adaptations*. All living things and the planet are dynamically adapting to one another physically, socially, and evolutionarily. Thus, the genetic adaptations exhibited by microbes to antimicrobials for their survival are akin to the social adaptations humans must adopt for their survival to planetary climate change, which itself may be considered the planet's adaptation to human activities. Hence, all forms of life on the planet, as well as the planet itself, are in a complex dance of adaptations to one another for survival. Thus, the concepts of adaptation and interconnection facilitate a framework that not only provides an understanding of the relationship between humans, the planet, and all life but can also help to identify the complex relationships between AMR and climate change.

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Anthropocene and Health

AMR is a major global challenge to health and our capacity to prevent and treat common infectious diseases is at risk. The World Health Organization (WHO) states that AMR is driven by the misuse and overuse of antimicrobials (among other factors) [1], and weak regulation of over-the-counter medicines and inappropriate prescribing of AMs are identified as key health system challenges [2]. Whilst modern expectations of health and longevity have been made easier because of antibiotics, the achievements of modern medicine may be compromised as major surgery, cancer chemotherapy and organ transplants will become much more dangerous in the absence of effective antibiotics.

1.27 million deaths were caused by bacterial antimicrobial resistance (AMR) globally in 2019, with AMR infections associated with almost 5 million more [3]. In 2050, 1.91 million deaths attributable to and 8.22 million deaths associated with AMR may occur globally [4] with estimated annual costs of $2 trillion USD [5].

AMR has been identified as a "One Health" challenge, which means that the interactions between the health of humans, animals, plants and the wider environment must be addressed through multisectoral and interdisciplinary approaches. (N.B. The One Health field has long recognised the importance of human, animal and environmental interactions in AMR, but Planetary Health goes further, considering aspects of intergenerational justice and future risk, for example.) 73% of global AM use is for livestock, [6] and antibiotics continue to be used to promote animal growth [7].

It is important to understand how human health is impacted by other challenges of life in the 'Anthropocene' - a term used to describe the modern, human-modified world that has deviated from the natural environment we are adapted to through evolution – and how these intersect with AMR and climate change. For example, longer lives mean more people live into older age, when immune systems may be weaker and more at risk from pathogens; food may spoil more quickly in hotter temperatures leading to greater risk from foodborne pathogens; conditions such as cystic fibrosis can be lived with but at a cost to antibiotic usage.

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Systems Thinking and Complexity

Complex Adaptive Systems thinking identifies all elements of any given phenomenon, as well as the various interactions between these elements that can result in the emergence of new elements and processes, particularly for dynamic systems that experience ongoing adaptations. Complex and intractable challenges necessitate complex adaptive systems thinking, particularly when examining climate change and AMR, both separately and jointly. According to Iyer et al., systems thinking 'organises the understanding of complex systems through four dimensions: distinctions, systems, relationships, and perspectives. In this framework, distinctions refer to how elements in a system have identities and can be grouped by what they are not, systems refer to elements that may be parts or a whole, relationships refers to associations between elements and their causal ordering, and perspectives refers to the viewpoint from which elements are analysed' [1]. Systems Thinking and Complexity is a central component of the planetary health model that is essential to 'characterise the linkages between environmental changes and human health at different geospatial and temporal scales [2].

Complex systems analysis can be identified throughout the Planetary Health Framework, particularly in terms of:

a) the interdependence of environmental, social, cultural, and other factors;
b) the spatial and temporal scales and levels of analysis required;
c) Feedback loops inherent in environmental processes; and
d) the transdisciplinarity and cross-disciplinary 'language' essential to provide a full understanding of the factors and the methods to redress these complex challenges. [3]

Systems thinking in a planetary health framework helps identify key relationships between the different types of factors; provides an understanding of cascading effects between different parts of a system; and fosters holistic solutions that can identify root causes and locations for intervention [4].

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Equity and Social Justice

A recent European Health Observatory publication on socioeconomic drivers of AMR [1] identified several critical socioeconomic drivers of AMR: gender; living conditions; education level; healthcare access; governance; human mobility; conflict; agriculture and pollution … and, of course, climate change, which already impacts vulnerable populations disproportionately.

Just a handful of issues at the intersection of climate change, AMR and social justice include:

- The all-ages mortality from AMR in Sub-Saharan Africa is > twice that of Western Europe.
- ~45% of LMIC healthcare facilities do not have clean, potable water from a tap, despite hygiene playing a major role in infection control and prevention.
- Planetary Health discourse is dominated by Global North voices and conventions, despite evidence of the value of indigenous worldviews in reshaping policy and societal attitudes.[2]
- Neglect of tropical diseases not considered a threat to the Global North (despite growing evidence of vectors ranging further north [3, 4] and the intersection of disease reservoirs in communities living in extreme poverty or homelessness [5] amid otherwise affluent societies with AMR, both create vulnerabilities for AMR emergence and spread.

Nor does only equity between the Global North and Global South, or between the rich and poor within society need to be addressed (more than ever since the removal of much US international aid and WHO funding): so too does equity between human and non-human animals need to be considered. Livestock animals currently kept in unsanitary, overcrowded, poor welfare conditions in which disease flourishes [6], driving up often irrational and poorly regulated antibiotic use, also deserve justice but the One Health field tends to focus more on alternatives to antibiotics that do not address the underlying problem, which requires a transformational shift in dietary practice [7], itself tied to issues of food equity.

AMR also has parallels with climate change in terms of transgenerational fairness, with past and current generations producing intractable challenges for future generations through their widespread use across multiple sectors.

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Movement Building and Systems Change

The global response to AMR has resulted in multi-sectoral initiatives and global guidelines that stipulate the critical actions required to address it. Both prescribers and users have become too dependent on antimicrobial agents to manage human and animal disease [1], and there is a widespread lack of understanding of the dangers of antimicrobial resistance and its impact. Despite most countries globally having National Action Plans on AMR, implementation and enforcement is often challenging. A 2022 analysis of global guidance [2] proposes a framework of action, highlighting the need for interdisciplinary action across 8 key thematic areas:

1. Optimise the use of antimicrobials in humans and animals
2. Develop new drugs, diagnostics and vaccines
3. Understand AMR in the environment
4. Reduce and prevent infection in humans and animals
5. Optimise AMR surveillance and data management
6. Increase financial investment in AMR related activities
7. Establish strong AMR governance AND
8. Increase public engagement with AMR

Within the final category of public engagement, three distinct actions were identified: systematic and meaningful engagement of public and civil society groups, increasing public awareness, and educating the public – the purpose of this being to identify how to engage with behaviour change in relation to antimicrobials.

One Health is often mentioned in an AMR context and most AMR Action Plans stress the importance of One Health. However, the links with animals and the environment are often poorly articulated, with even the “animal health” and “environmental health” labels suggesting that concerns lie with the health of animals and the environment themselves, rather than their integral roles in the origin, evolution and transmission of AMR that ultimately leads to human deaths from antibiotic resistant infections. We are investigating whether Planetary Health thinking can contribute to better understanding and communication of the complex transdisciplinary problem of AMR.

An ‘AMR movement’ is emerging with a focus on antimicrobial stewardship, but starting to incorporate discussions on food production and environmental protection. The Planetary Health Alliance Roadmap presents a framework for individuals and communities to act to address critical societal challenges.

A key input into this Working Group will be findings from the other Working Groups: in particular, what needs to be communicated, who the key stakeholders are, and what gaps still

exist. The Working Group will also need to think about transdisciplinarity: how to communicate concepts across disciplines that may not have a common language.

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Other key reading

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