GLOBAL CHANGE
CONSENSUS STATEMENT

Scientists' warning to humanity: microorganisms and climate change

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Abstract | In the Anthropocene epoch in which we now live, climate change is impacting most life on Earth. Microorganisms support the existence of all higher trophic life forms. In order to understand how humans and other life forms on Earth (including those we are yet to discover) can withstand anthropogenic climate change, it is vital to incorporate knowledge of the microbial 'unseen majority'. We must learn not just how microorganisms affect climate change (including production and consumption of greenhouse gases), but also how microorganisms will be affected by climate change and other human activities. This Consensus Statement documents the central role and global importance of microorganisms in climate change biology. It also puts humanity on notice that the impact of climate change will rely heavily on responses of microorganisms, which are essential for achieving an environmentally sustainable future.

Introduction

Human activities and their effects on the climate and environment cause unprecedented animal and plant extinctions, loss in biodiversity[1,2,3,4] and endanger animal and plant life on Earth[5]. Losses of species, communities and habitats are comparatively well researched, documented and publicized[6]. By contrast, microorganisms are generally not discussed in the context of climate change (particularly the effect of climate change on microorganisms). While invisible to the naked eye and thus somewhat intangible[7], the abundance (~10^{30} total bacteria and archaea)[8] and diversity of microorganisms underlie their role in maintaining a healthy global ecosystem: simply put, the microbial world constitutes the life support system of the biosphere. Although human effects on microorganisms are less obvious and certainly less characterized, a major concern is that changes in microbial biodiversity and activities will affect the resilience of all other organisms and hence their ability to respond to climate change[9].

Microorganisms have key roles in carbon and nutrient cycling, animal (including human) and plant health, agriculture and the global food web. Microorganisms live in all environments on Earth that are occupied by macroscopic organisms, and they are the sole life forms in other environments, such as the deep subsurface and 'extreme' environments. Microorganisms date back to the origin of life on Earth at least 3.8 billion years ago, and they will likely exist well beyond any future extinction events.

Although microorganisms are crucial in regulating climate change, they are rarely the focus of climate change studies and are not considered in policy development. Their immense diversity and varied responses to environmental change make determining their role in the ecosystem challenging. In this Consensus Statement, we illustrate the links between microorganisms, macroscopic organisms and climate change, and put humanity on notice that the microscopic majority can no longer be the unseen 'elephant' in the room. Unless we appreciate the importance of microbial processes, we fundamentally limit our understanding of the Earth's bio-sphere and response to climate change and thus jeopardize efforts to create an environmentally sustainable future[6] (BOX 1).

Scope of the Consensus Statement

In this Consensus Statement, we address the effects of microorganisms on climate change, including microbial climate-active processes and their drivers. We also address the effects of climate change on microorganisms, focusing on the influences of climate change on microbial community composition and function, physiological responses and evolutionary adaptation. Although we focus on microorganism-climate connections, human activities with a less direct, but possibly synergistic effect, such as via local pollution or eutrophication are also addressed.

For the purpose of this Consensus Statement, we define microorganism as any microscopic organism or virus not visible to the naked eye (<50 µm) that can exist in a unicellular, multicellular (for example, differentiating species), aggregate (for example, biofilm) or viral form. In addition to microscopic bacteria, archaea, eukaryotes and viruses, we discuss certain macroscopic unicellular eukaryotes (for example, larger marine phytoplankton) and wood decomposing fungi. Our intent is not to exhaustively cover all environments nor all anthropogenic influences but to provide examples from major global biomes (marine and terrestrial) that highlight the effects of climate change on microbial processes and the consequences. We also highlight agriculture and infectious diseases and the role of microorganisms in climate change mitigation. Our Consensus Statement alerts microbiologists and non-microbiologists to address the roles of microorganisms in accelerating or mitigating the impacts of anthropogenic climate change (BOX 1).

Conclusion

Microorganisms make a major contribution to carbon sequestration, particularly marine phytoplankton which fix as much net CO_2 as terrestrial plants. For this reason, environmental changes that affect marine microbial photosynthesis and subsequent storage of fixed carbon in deep waters are of major importance for the global carbon cycle. Microorganisms also contribute substantially to greenhouse gas emissions via heterotrophic respiration (CO_2), methanogenesis (CH_4) and denitrification (N_2O).

Many factors influence the balance of microbial greenhouse gas capture versus emission, including the biome, the local environment, food web interactions and responses, and particularly anthropogenic climate change and other human activities (FIGS. 1–3).

Human activities that directly affect microorganisms include greenhouse gas emissions (particularly CO_2, CH_4 and N_2O), pollution (particularly eutrophication), agriculture (particularly land usage), and population growth, which positively feeds back on climate change, pollution, agricultural practice and the spread of disease. Human activity that alters the ratio of carbon uptake relative to release will drive positive feedbacks and accelerate the rate of climate change. By contrast, microorganisms also offer important opportunities for remedying human caused problems through improved agricultural outcomes, production of biofuels and remediation of pollution.

Addressing specific issues involving microorganisms will require targeted laboratory studies of model microorganisms (BOX 2). Laboratory probing of microbial responses should assess environmentally relevant conditions, adopt a 'microbcentric' view of environmental stressors and be followed up by field tests. Mesocosm and in situ field experiments are particularly important for gaining insight into community level responses to real environmental conditions. Effective experimental design requires informed decision-making, involving knowledge from multiple disciplines specific to marine (for example, physical oceanography) and terrestrial (for example, geochemistry) biomes.

To understand how microbial diversity and activity that govern small scale interactions translate to large system fluxes, it will be important to scale findings from individuals, to communities and to whole ecosystems. Earth system modellers need to include microbial contributions that account for physiological and adaptive (evolutionary) responses to biotic (including other microorganisms, plants and organic matter substrates) and abiotic (including mineral surfaces, ocean physics and chemistry) forcings.

We must improve our quantitative understanding of the global marine and soil microbiome. To understand biogeochemical cycling and climate change feedbacks at any location around the world, we need quantitative information about the organisms that drive elemental cycling (including humans, plants and microorganisms), and the environmental conditions (including climate, soil physiochemical characteristics, topography, ocean temperature, light, and mixing) that regulate the activity of those organisms. The framework for quantitative models exists, but to a large extent these models lack mechanistic details of marine and terrestrial microorganisms. The reason for this omission has less to do with how to construct such a model mathematically, but instead stems from the paucity of physiological and evolutionary data enabling robust predictions of microbial responses to environmental change. A focused investment into expanding this mechanistic knowledge represents a critical path toward generating the global models essential for benchmarking, scaling and parameterizing Earth System Model predictions of current and future climate.

Extant life has evolved over billions of years to generate vast biodiversity and microbial biodiversity is practically limitless compared to macroscopic life. Biodiversity of macroscopic organisms is rapidly declining because of human activity, suggesting that the biodiversity of host-specific microorganisms of animal and plant species will also decrease. However, compared to macroscopic organisms we know far less about the connections between microorganisms and anthropogenic climate change. We can recognize the effects of microorganisms on climate change and climate change on microorganisms, but what we have learned is incomplete, complex and challenging to interpret. It is therefore not surprising that challenges exist for defining causes and effects of anthropogenic climate change on biological systems. Nevertheless, there is no doubt that human activity is causing climate change, and this is perturbing normal ecosystem function around the globe (BOX 1). Across marine and terrestrial biomes, microbially-driven greenhouse gas emissions are increasing and positively feeding back on climate change. Irrespective of the fine details, the microbial compass points to the need to act (BOX 2). Ignorance about the role of, effects on, and feedback response of microbial communities to climate change can lead to our own peril. An immediate, sustained, and concerted effort is required to explicitly include microorganisms in research, technology development, and policy and management decisions. Microorganisms not only contribute to the rate of climate change, they can also contribute immensely to its effective mitigation and our adaptation tools.

Box 1 | **Scientists' warning**

The Alliance of World Scientists and the Scientists' Warning Movement was established to alert humanity to the impacts of human activities on global climate and the environment. In 1992, 1,700 scientists signed the first Warning, raising awareness that human impact puts the future of the living world at serious risk[267]. In 2017, 25 years later, the Second Warning was issued in a publication signed by more than 15,000 scientists[5]. The movement has continued to grow with more than 21,000 scientists endorsing the Warning. At the heart of the Warning is a call to governments and institutions to shift policy away from economic growth and towards a conservation economy that will stop environmental destruction and enable human activities to achieve a sustainable future[268]. Linked to the Second Warning is a series of articles that will focus on specific topics, the first of which describes the importance of conserving wetlands[269]. A film, The Second Warning, also aims to document scientists' advocacy for humanity to replace 'business as usual' and take action to achieve the survival of all species by averting the continuing environmental and climate change crisis.

Complementing the goals of the Alliance of World Scientists are the United Nations Sustainable Development Goals which have been formulated to realize dignity, peace and prosperity for people and the planet, now and into the future[6]. The goals are framed around environmental, economic and social needs, and address sustainability through the elimination of poverty, development of safe cities and an educated populations, implementation of renewables (energy generation and consumption), and urgent action on climate change involving equitable use of aquatic and terrestrial systems to achieve a healthy, less polluted biosphere. The goals recognize that responsible management of finite natural resources are required for the development of resilient, sustainable societies.

Our Consensus Statement represents a warning to humanity from the perspective of microbiology. As a Microbiologists' Warning, the intent is to raise awareness of the microbial world and make a call to action for microbiologists to become increasingly engaged in, and microbial research to become increasingly integrated into the frameworks for addressing climate change and accomplishing the United Nations Sustainable Development Goals (BOX 2). It builds on previous science and policy efforts to call attention to the role of microorganisms in climate change[7,126,270–272] and their broad relevance to society[7]. Microbiologists are able to endorse the Microbiologists's Warning by becoming a signatory.

Box 2 | **A call to action**

The Microbiologists' Warning calls for:

- Greater recognition that all multicellular organisms, including humans, rely on microorganisms for their health and functioning; microbial life is the support system of the biosphere.
- The inclusion of microorganisms in mainstream climate change research, particularly research addressing carbon and nitrogen fluxes.
- Experimental design that accounts for environmental variables and stresses (biotic and abiotic) that are relevant to the microbial ecosystem and climate change responses.
- Investigation of the physiological, community, and evolutionary microbial responses and feedbacks to climate change.
- A focus on microbial feedback mechanisms in the monitoring of greenhouse gas fluxes from marine and terrestrial biomes, agricultural, industrial, waste and health sectors and investment in long-term monitoring.
- Incorporation of microbial processes into ecosystem and Earth System models to improve predictions under climate change scenarios.
- The development of innovative microbial technologies to minimize and mitigate climate change impacts, reduce pollution, and eliminate reliance on fossil fuels.
- The introduction of teaching of personally, societally, environmentally and sustainability relevant aspects of microbiology in school curricula, with subsequent up-scaling of microbiology education at tertiary levels, to achieve a more educated public and appropriately trained scientists and workforce.
- Explicit consideration of microorganisms for the development of policy and management decisions.
- A recognition that all key biosphere processes rely on microorganisms and are greatly affected by human behaviour, necessitating an integration of microbiology in the management and advancement of United Nations Sustainable Development Goals.

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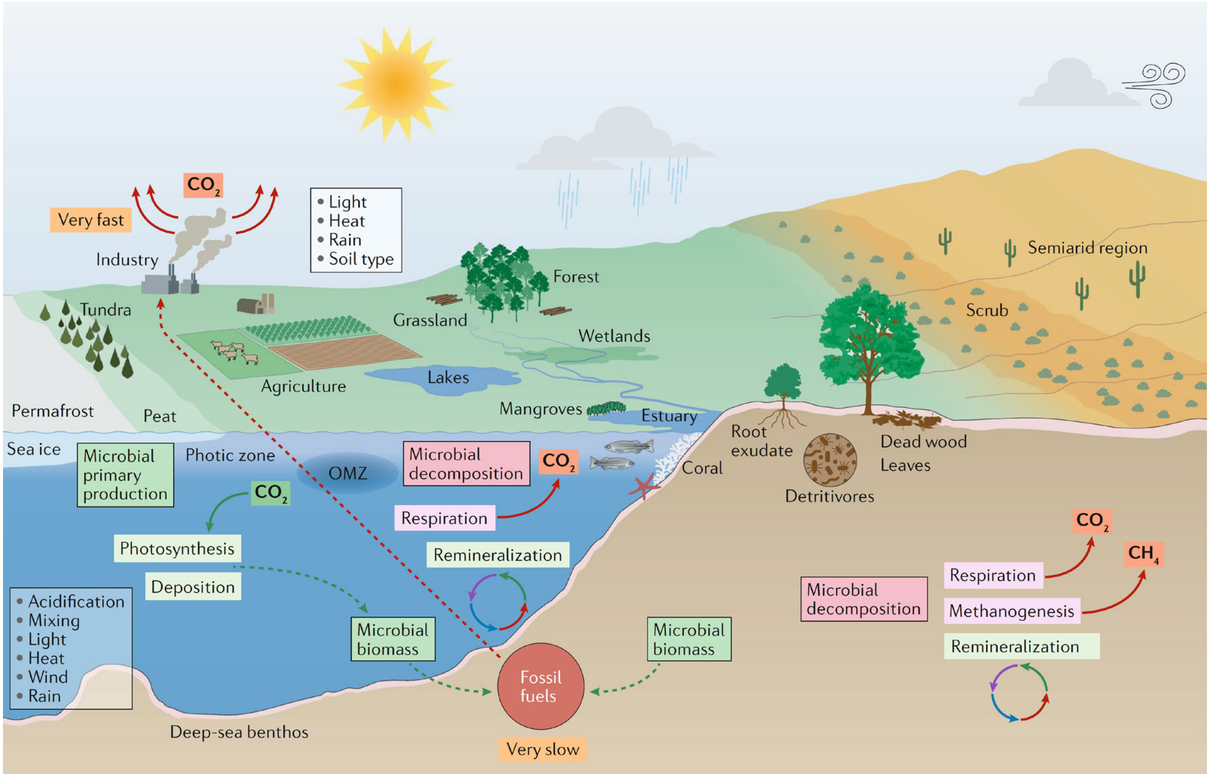

Fig. 1 | **Microorganisms and climate change in marine and terrestrial biomes.** In marine environments, microbial primary production contributes substantially to CO_2 sequestration. Marine microorganisms also recycle nutrients for use in the marine food web and in the process release CO_2 to the atmosphere. In a broad range of terrestrial environments, microorganisms are the key decomposers of organic matter and release nutrients in the soil for plant growth, as well as CO_2 and CH_4 into the atmosphere. Microbial biomass and other organic matter (remnants of plants and animals) is converted to fossil fuels over millions of years. By contrast, burning of fossil fuels liberates greenhouse gases in a small fraction of that time. As a result, the carbon cycle is extremely out of balance and atmospheric CO_2 levels will continue to rise as long as fossil fuels continue to be burned. The many effects of human activities, including agriculture, industry, transport, population growth and human consumption, combined with local environmental factors, including soil type and light, greatly influence the complex network of microbial interactions that occur with other microorganisms, plants and animals. These interactions dictate how microorganisms respond to and affect climate change (for example, through greenhouse gas emissions) and how climate change (for eample, higher CO_2 levels, warming, and precipitation changes) in turn affect microbial responses.

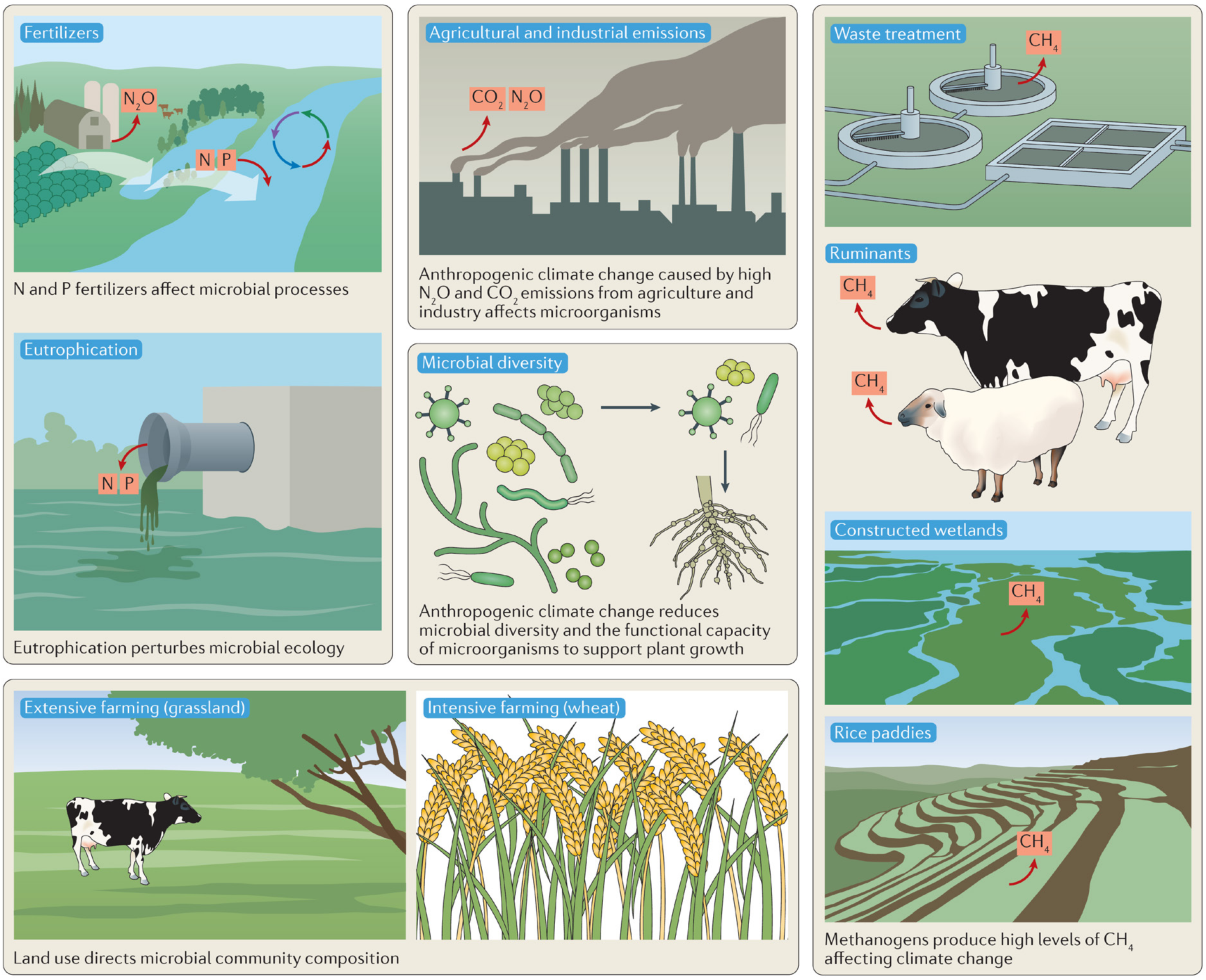

Fig. 2 | **Agriculture and other human activities that affect microorganisms.** Agricultural practices influence microbial communities in specific ways. Land usage (for example, plant type) and sources of pollution (for example, fertilizers) perturb microbial community composition and function, thereby altering natural cycles of carbon, nitrogen and phosphorous transformations. Methanogens produce substantial quantities of methane directly from ruminant animals (for example, cattle, sheep and goats) and saturated soils with anaerobic conditions (for example, rice paddies and constructed wetlands). Human activities that cause a reduction in microbial diversity also reduce the capacity for microorganisms to support plant growth.

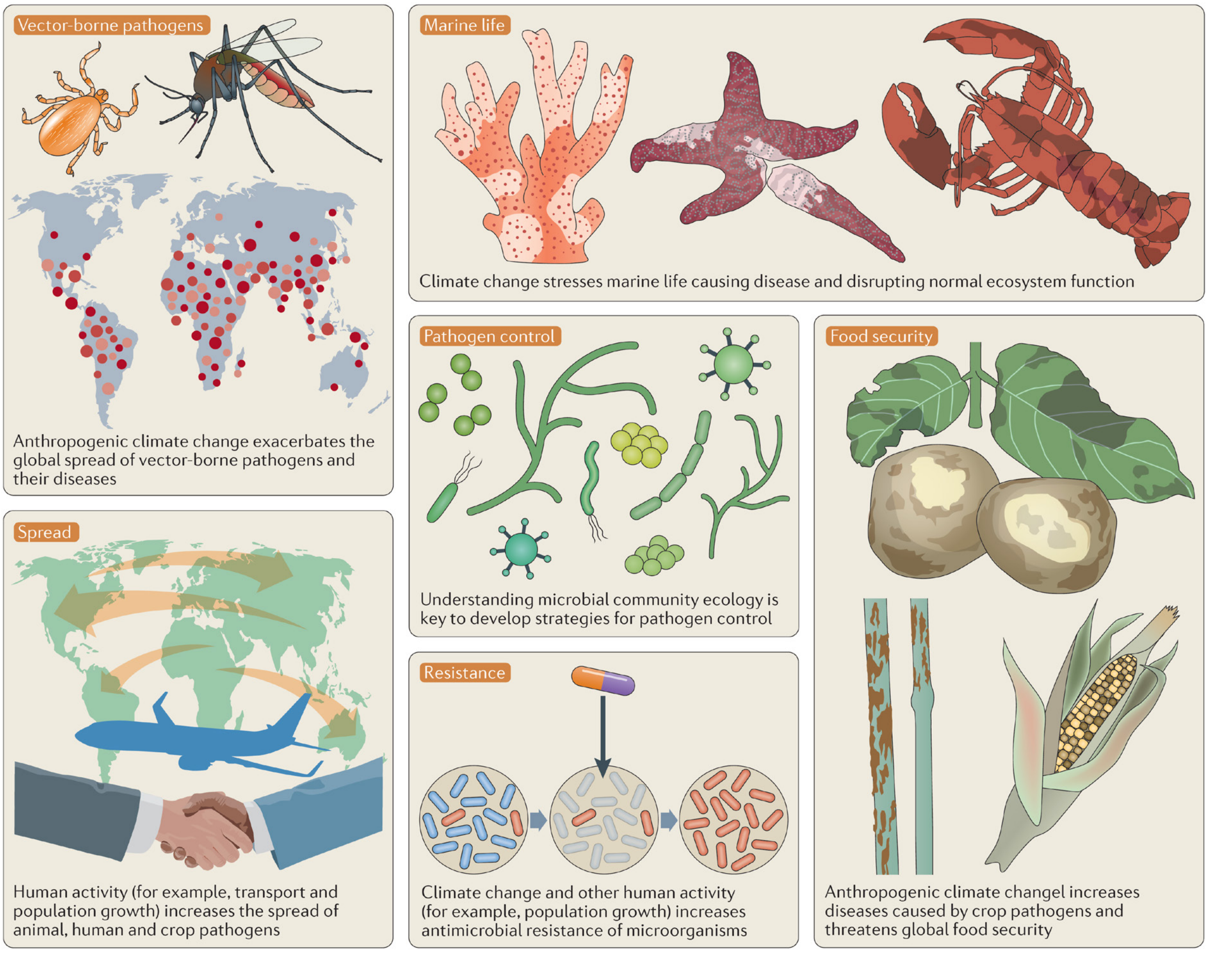

Fig. 3 | **Climate change exacerbates the impact of pathogens.** Anthropogenic climate change stresses native life thereby enabling pathogens to increasingly cause disease. The impact on aquaculture and crops threatens global food supply. Human activities, such as population growth and transport, combined with climate change increase antibiotic resistance of pathogens and the spread of waterborne and vector-borne pathogens, thereby increasing diseases of humans, other animals, and plants.