Global Environmental Change

Microbial Contributions
Microbial Solutions

AMERICAN SOCIETY FOR MICROBIOLOGY

Global Environmental Change
Microbial Contributions, Microbial Solutions

Contributing Authors

Gary M. King, Ph.D., Chair, Subcommittee on Global Environmental Change
University of Maine

David Kirchman, Ph.D., University of Delaware

Abigail A. Salyers, Ph.D., University of Illinois

William Schlesinger, Ph.D., Duke University

James M. Tiedje, Ph.D., Chair, Committee on Environmental Microbiology
Michigan State University

About the American Society for Microbiology

The American Society for Microbiology (ASM) is the largest single life science society, composed of over 42,000 scientists, teachers, physicians, and health professionals. The ASM's mission is to promote research and research training in the microbiological sciences and to assist communication between scientists, policymakers, and the public to improve health, economic well being, and the environment. The goal of this booklet is to provide background information on the problem of global environmental change and to emphasize the critical role of research in responding to environmental and public health issues which currently confront policymakers.

Introduction

Global change is a natural phenomenon and contemporary problem

. . . the basic chemistry of Earth's surface is determined by biological activity—especially that of microbes, so we must look to studies of microbiology to help us understand global change and to find solutions for undesirable changes.

With each breath, we inhale gases produced by microbes, including the oxygen so vital to our existence. However, microbes also produce carbon dioxide (CO_2), methane and nitrous oxide, all of which are important atmospheric gases that in elevated amounts contribute to global warming. What causes the current unprecedented production of these so-called greenhouse gases? Certainly humans have been directly responsible for many major changes, especially those leading to excess CO_2 production and stratospheric ozone destruction. But have humans somehow altered the environment and caused microbes to produce more gases too? Do microbes amplify or worsen problems created by humans? Can we manage microbial activity to slow or halt the adverse effects of greenhouse gas production and other global changes?

Clearly future generations may experience an atmosphere different from our own as the Earth undergoes unusually rapid changes. Carbon dioxide concentrations were relatively stable for the past 10,000 years but then began to increase rapidly about 150 years ago (from 270 parts per million in the mid-1800s to about 360 ppm today) as a result of fossil fuel consumption and land use change. Carbon dioxide concentrations are now increasing at about 0.4 percent each year for the same reasons. The increase in atmospheric methane is even greater, about 1 percent annually. Previously, microbes helped maintain stable conditions in the atmosphere; microbes will undoubtedly help stabilize atmospheric conditions in the future. However, human actions have altered microbial activity on a global scale and inadvertently caused significant changes in the composition of the atmosphere.

Of course, changes in atmospheric composition are but one component of global change, which also includes disturbances in the physical and chemical conditions of the oceans and land surface. Although global change has been a natural process throughout Earth's history, humans are responsible for substantially accelerating present-day changes. These changes may adversely affect human health and the biosphere on which we depend. Many changes involve microbes that contribute to or amplify human impacts. Since the basic chemistry of Earth's surface is determined by biological activity—especially that of microbes—we must look to studies of microbiology to help us understand how and why the Earth is changing and to find solutions for undesirable changes. Unless we understand better the human-microbe partnership in global change, and better manage activities of organisms that maintain balances in the atmosphere and biosphere, we will find ourselves increasingly challenged by unprecedented environmental problems.

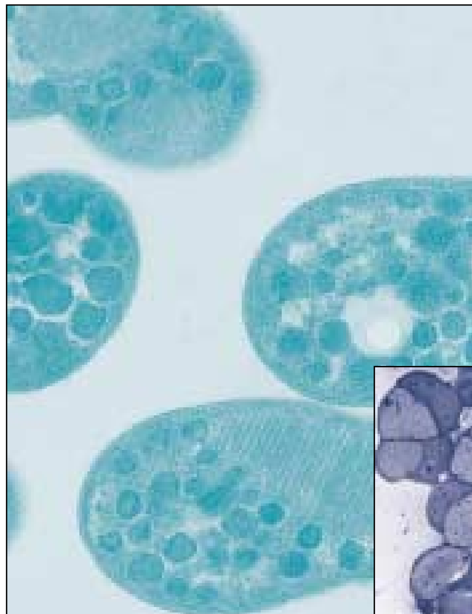
Microbes have changed the composition of the atmosphere since the origin of life. As early as 3.8 billion years ago, primitive blue-green algae or cyanobacteria may have produced Earth's first molecular oxygen. The oxygen reacted with dissolved iron in the primitive oceans, creating massive deposits of oxidized iron in rust-colored sediment bands known as the Banded Iron Formations. Thus, we can thank microbes for producing some of the richest metal deposits within the Earth's crust. In addition, as oxygen began to accumulate in the atmosphere, a variety of new and more complex life forms emerged, particularly those that could use oxygen to enhance their metabolic activity. Oxygen in Earth's atmosphere also allowed for development of the ozone layer, which shielded the Earth's surface from harmful ultraviolet rays and promoted colonization of the land. Earth's early photosynthetic microbes thereby paved the way for the evolution of all higher forms.

Banded Iron Formation. Microbes have produced rich metal deposits within the Earth's Crust.

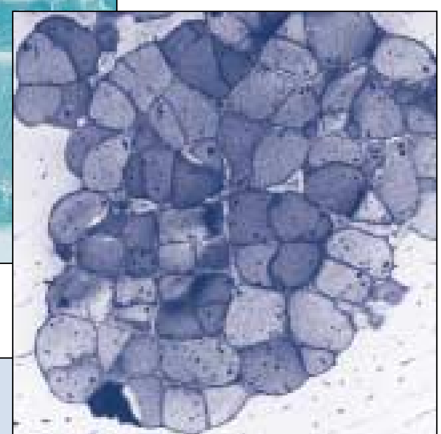
Microbes and Global Change

Microbes play numerous key roles in global change, often as silent partners in human activities such as agriculture, mining and waste treatment

Complex interactions among humans, microbes and the rest of the biosphere have created some of our most challenging global problems. Recent discoveries reveal that human activities can dramatically affect the role of microbes in Earth's climate. Human-induced warming and other environmental changes alter greenhouse gas production by microbes and intensify ongoing global shifts in climate. For instance, elevated temperatures may increase both methane and CO_2 emissions from the vast northern peatlands, leading to further increases in warming. Interactions such as these among humans, microbes and climate need careful consideration since they can significantly worsen climate change and seriously hinder ongoing and planned efforts to minimize climate-related problems.



Methanotrophic bacteria. This bacterium helps regulate atmospheric methane concentrations by reducing methane emissions from wetlands and removing methane directly from the atmosphere. (Courtesy of John Sieburth, University of Rhode Island)



Methanosarcina barkeri. Methanogenic bacteria are almost exclusively responsible for producing methane that is emitted to the atmosphere from both natural and human-engineered systems. (Courtesy of Henry Aldrich, University of Florida)

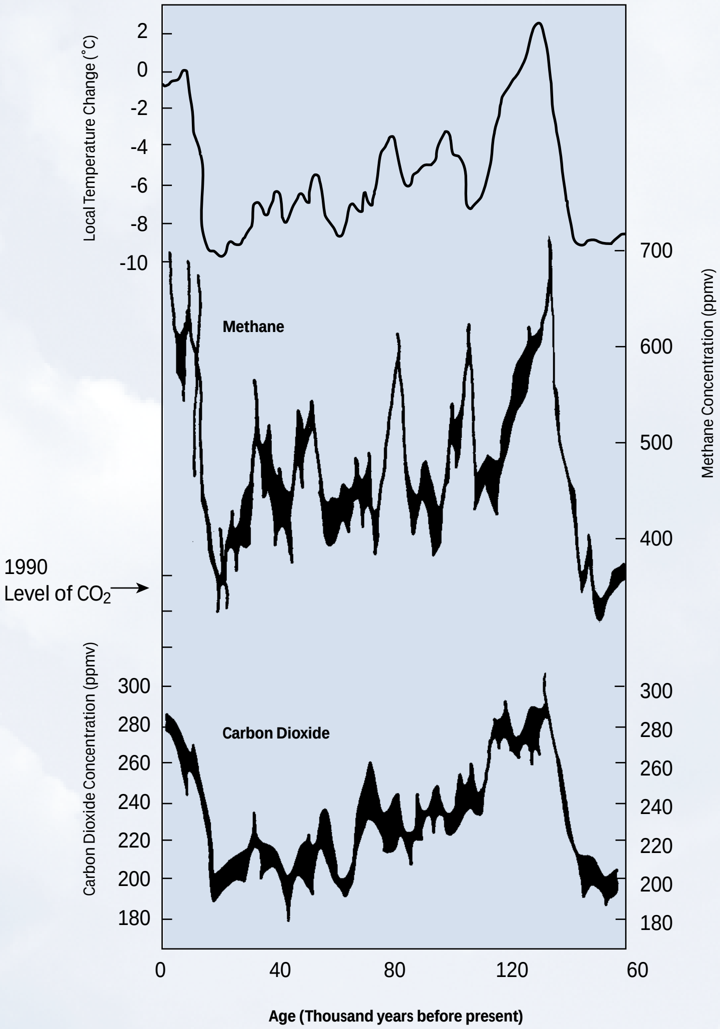
Biological Contributions to Atmospheric Composition

Numerous biological and chemical processes contribute to atmospheric composition. For many gases microbes are major sources or sinks, as is indicated by the relative importance of different contributors (numbers in parentheses). Contributions from humans include direct inputs and removal (e.g., fossil fuel combustion, ammonia production from nitrogen), but also involve processes that significantly affect microbial inputs and removal (e.g., waste treatment and agriculture).

Gas	Inputs From	Removal By	% Annual Change
Nitrogen	Microbes (100)	Microbes (53)	Negligible Lightening (6) Humans (41)
Oxygen	Microbial algae (50) Plants (50)	Microbes (90) Animals (10)	Negligible
Carbon Dioxide	Microbes (86) Animals (10) Humans (4)	Microbial algae (50) Plants (50)	+ 0.4%
Methane	Microbes (26) Animals (17) Humans (57)	Microbes (10) Atm chemistry (90)	+ 1%
Nitrous oxide	Microbes (50) Humans (50)	Microbes (?) Atm chemistry (100?)	+ 0.3%

Atmospheric Composition Over Time from Ice Core Records

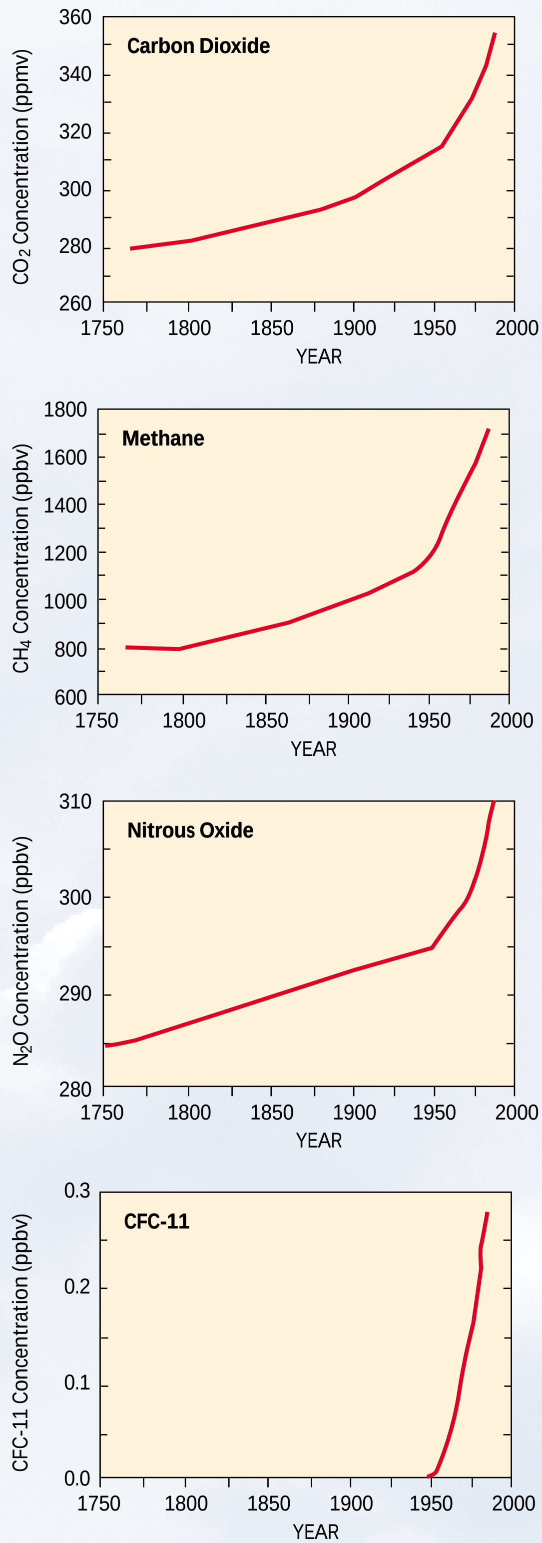
Gases trapped in Antarctic ice reveal natural changes in atmospheric composition coincident with changes in climate. Carbon dioxide (CO_2) and methane concentrations rise during warm periods and decrease during colder periods.



Ice core records (top) allow reconstruction of natural changes in greenhouse gases and temperature for thousands of years. These records reveal that changes occurred relatively slowly over many centuries to millennia. In contrast, records of greenhouse gas concentrations for the past 50-100 years (right) reveal unprecedented rates of change that significantly exceed previous natural variations.

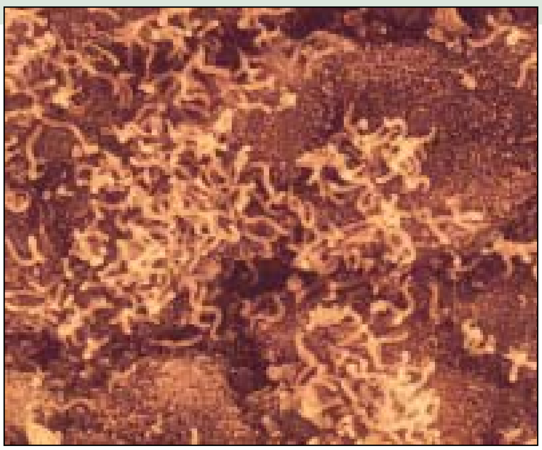
Contemporary Changes in Atmospheric Trace Gases

Contemporary records of atmospheric composition show concentrations of major greenhouse gases increasing at rates substantially greater than those recorded in ice cores.



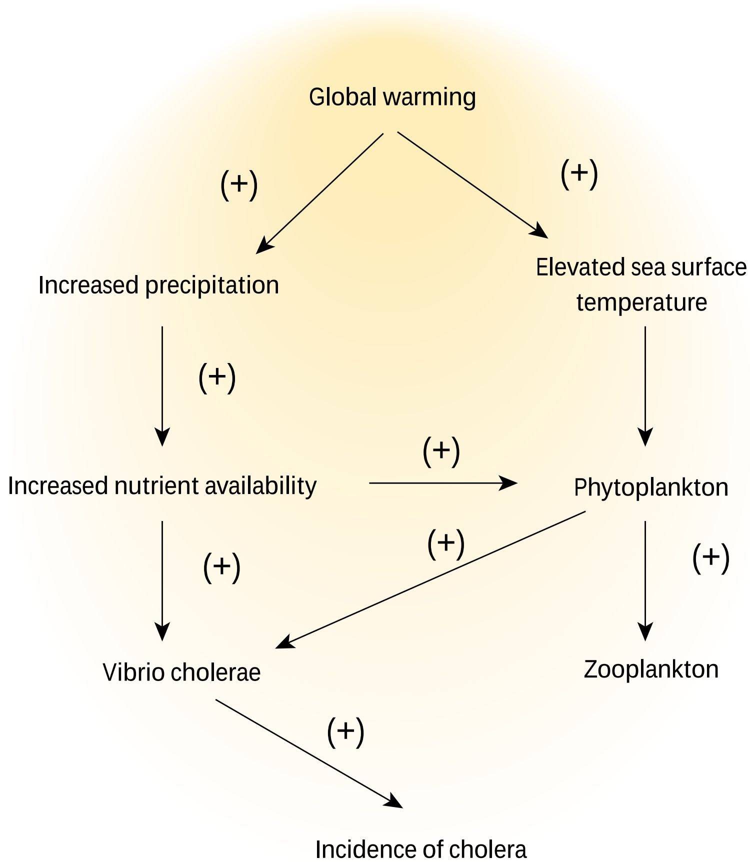
Examples of climate change and emerging microbial diseases

Disease	Microbe	Relationship to Climate Change
Bubonic plague	Yersinia pestis	Changes from dry to wet conditions that increase populations of rodent/flea vectors
Cholera	Vibrio cholerae	Associated with some phytoplankton blooms in nutrient-rich coastal waters; blooms vary with changing precipitation regimes and El Nino
Lyme disease	Borrelia burgdorferii	Associated with conditions that increase deer/tick vectors
Encephalitis	West Nile Virus	Associated with conditions that increase mosquito vectors



V. cholerae. The distributions and health threats of many disease-causing organisms, such as the agent for cholera, are linked to climate.

Relationships among atmospheric composition, climate change and human, animal and plant health merit serious study. Outbreaks of a number of diseases, including Lyme disease, hantavirus infections, dengue fever, bubonic plague, and cholera, have been linked to climate change. Fluctuations in disease incidence can be related to climate-dependent changes in the numbers of pathogen vectors such as mosquitoes, ticks and rodents. Changes in mosquito populations are especially concerning since mosquito-borne microbial diseases kill a large fraction of the human population. Climate change can also directly affect the distribution and abundance of pathogens themselves, thus increasing the prevalence of disease in humans, animals and plants.



Complex relationships between cholera and climate. Changes in climate affect physical parameters (precipitation and water temperature) that result in cascading effects that can increase the abundance of cholera-causing bacteria and the incidence of the disease.

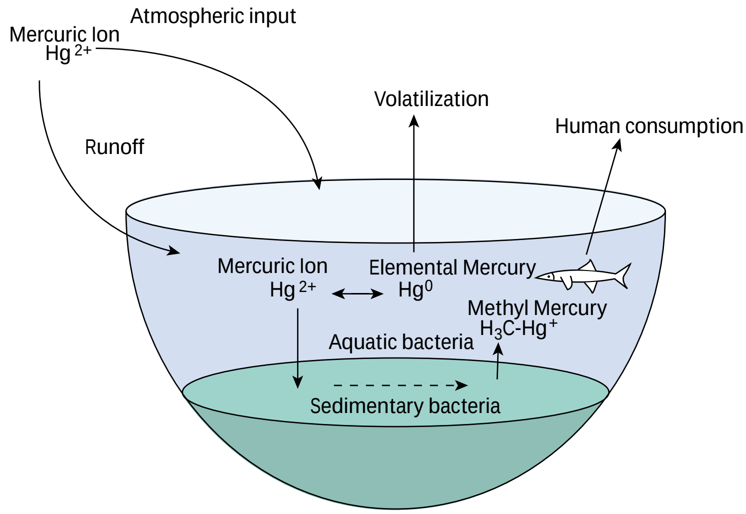
Relationship between sea-surface temperature (SST) and cholera case data in Bangladesh from January to December 1994.

Reprinted with permission from Colwell, Rita R. "Global Climate and Infectious Disease: The Cholera Paradigm" *Science Vol. 274,* 20 December 1996. Pages 2025–31. Copyright 1997 American Association for the Advancement of Science.

Microbes respond to a variety of other disturbances within the biosphere. Although the exact mechanisms are sometimes unclear the consequences can be positive or negative. We know that microbes in general mediate numerous biogeochemical reactions, and in aquatic systems form the base of food chains that sustain organisms from fish to humans. Terrestrial and aquatic microbes also significantly influence global conditions, which is hardly surprising since microbes outnumber by far all other organisms in rivers, lakes, oceans, and on the land. Some of these microbes react to human disturbances by mobilizing toxic elements such as mercury, selenium and arsenic, producing unexpected serious environmental problems. For example, microbes convert dissolved mercury into a highly toxic, volatile form that disperses through the atmosphere with global consequences. Other microbes can detoxify a variety of hazardous pollutants and elements introduced into the environment by human activity. However, the net balance of human-caused disturbances on aquatic and terrestrial microbes and their many activities, deleterious and beneficial, is unknown. Nonetheless, it is clear that the microbial world responds to human activity with results that often are surprising and highly undesirable.

Massive algal blooms resulting from excess nitrogen and phosphorous carried into rivers, lakes and oceans are one of the consequences of human activity. Large blooms, such as those in the Gulf of Mexico, lead to aquatic oxygen depletion, substantially degrading marine ecosystems and limiting their use as sources of food, water and recreation. Some evidence suggests that "red tides," "brown tides" and other harmful algal blooms are increasing in frequency and severity. Blooms of a marine dinoflagellate, *Pfiesteria piscidica,* which have been linked to coastal pollution, were essentially unknown 20 years ago, but now produce large fish kills on the southeast coast of the United States.

Yet it is conceivable that algal blooms might be managed to reduce the impact of human-related CO_2 emissions. The intentional addition of iron nutrients in some areas of the ocean might stimulate algae to convert more atmospheric CO_2 into biomass. Ultimately this could lower CO_2 concentrations and reduce the greenhouse effect. Similar management of microbes and plants in terrestrial systems might also help to mitigate CO_2 accumulation. However, the complexities of numerous direct and subtle linkages among nutrient pollution, algal blooms, aquatic bacteria, disease, trace gases such as methane and nitrous oxide, climate, and human disturbances are only now beginning to be understood. Much more work is necessary before algal, plant and microbe management can be considered as a tool for climate control.

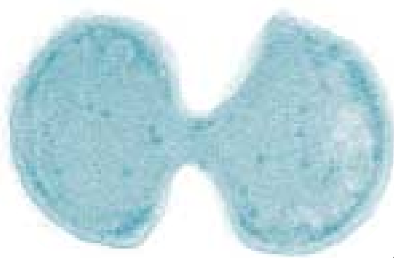


Aquatic Mercury Cycling. Bacteria in the water column and sediments transform mercury from natural and anthropogenic sources into forms that can be further mobilized or enter food chains resulting in severe impacts on animal and human health.

Acid mine drainage-impacted stream, Contrary Creek, Virginia. Coal and some mineral mining operations create conditions that promote microbial activity leading to the production of iron oxide deposits and sulfuric acid, which seriously degrade aquatic ecosystems.
(Courtesy of Aaron Mills, University of Virginia)

Microbiology Provides Solutions to Serious Environmental Challenges

Understanding, predicting and developing solutions for global environmental change are daunting scientific challenges, yet they must be met as other challenges have been in the past, to ensure that humans, animals and plants continue to thrive within the biosphere.



Brocadia anammoxidans, the bacterium responsible for anaerobic ammonia oxidation, which helps maintain the health of the biosphere (Courtesy of Michael Jetten, Delft University, Netherlands)

Microbiologists have worked for more than 100 years to understand interactions among microbes, humans, and their environment. They laid the foundation for a remarkable series of medical advances that have contributed to a 100 percent increase in human longevity since 1900. The increasing availability of microbial and human genome sequences, along with new ecological approaches to understanding disease, provide ample reason to expect continued success in dealing with potentially harmful microbes. Microbiologists also have made major contributions to improving the world in which humans live by managing microbes for waste management, agriculture, and industrial production. For example, landfills have been designed to maximize microbial decomposition while limiting adverse impacts on the atmosphere from methane emission; agricultural lands have been managed to promote desired microbial processes while decreasing those that are undesirable.

Collectively, these and many other past and present successes indicate that the discipline of microbiology has much to contribute in the future towards a greater understanding of global change and better solutions for a number of pressing environmental problems. Recent evidence for large decreases in the area and thickness of Arctic sea ice, for rapid and dramatic variations in past climate and ocean circulation, and for record temperatures leave no doubt that important change is occurring globally. While the ultimate magnitude of such change and its impact on humans and the biosphere remain uncertain, microbiologists can help to minimize them.

When faced with difficult environmental problems, microbiologists have learned that Nature often provides the most effective solutions. Wastewater treatment presents many serious problems since the effluent released from treatment plants must contain little organic matter or useable nitrogen. After a painstaking ten-year search, a group of Dutch microbiologists recently identified a novel microbe that converts two nitrogen-containing components of wastewater into harmless nitrogen gas. Anammox, the process this microbe uses for growth, has considerable promise for significantly improving the quality of wastewater effluents. Anammox could find broad applications in agriculture as well as in sewage treatment, and contribute to restoration of coastal and inland waters. Isolation of the anammox organism provides but one illustration of the extraordinary potential for microbiological research to help maintain the health of the biosphere.

Waste treatment plant. Microbiologists and engineers have successfully harnessed and optimized the use of various microbes to treat sewage and other forms of waste water.

Critical Research Needs

Microbes, responsible for transforming many of the Earth's most abundant compounds, cannot be ignored in the search for scientific solutions to adverse global changes.

Microbes are responsible for transforming many of the Earth's most abundant compounds, and thus are central to the global changes causing concern. Both the ubiquity of microbes and the delicacy of environmental balances contribute to the Earth's sensitivity to disturbances in the microbial world. Carbon compounds, methane, nitrogen and nitrogen oxides, as well as toxic elements such as mercury and arsenic, are part of the monumental production and recycling processes carried on by specialized microorganisms in our environment. However, despite their fundamental importance there are many uncertainties about microbes and the processes with which they are involved. Critical research problems include:

- Which microbes are responsible for producing and consuming specific environmentally important compounds and how does the diversity of microorganisms affect soil, water and atmospheric concentrations of various chemicals?

  A large fraction of atmospheric methane originates in or near roots of aquatic plants, including rice. What characteristics of methane-producing and -consuming bacteria promote activity in the rhizosphere? How does microbial diversity affect methane emissions? Nitrous oxide and nitric oxide are important gases for greenhouse warming and atmospheric chemistry. How does the diversity of microbes producing these gases vary among ecsoystems and in response to human disturbances?

- How and to what extent do microbes and their recycling processes respond to climate changes and other disturbances?

  Will warming and elevated atmospheric CO_2 concentrations lead to greater methane production and lower methane consumption? Can microbes be managed to enhance organic matter sequestration in soils and sediments to remove CO_2 from the atmosphere and reduce greenhouse warming? Can they be managed to reduce dependencies on synthetic fertilizers?

- How can information about activities occurring at the scale of microbes (micrometers to millimeters) be integrated across scales of communities, landscapes and ecosystems to help understand phenomena observed at global scales? What new technologies and computational systems are needed to facilitate integration and understanding across these scales?

Solutions to these and many other pressing problems will require intensive studies by microbial ecologists, physiologists, and geneticists working in partnership with scientists from many other disciplines. By working in broad, multidisciplinary research programs coordinated by scientists and policy makers, microbiologists can provide answers for a question of fundamental importance: How can microbial populations and activities be managed to sustain the biosphere and its diverse life forms while promoting human welfare?

Federal agencies, including the Department of Energy, the National Science Foundation, the United States Department of Agriculture, the Environmental Protection Agency, the National Aeronautical and Space Administration, and the National Institutes of Health, and collaborators in universities and the private sector, are currently engaged in major research programs on the microbiology of global change, bioremediation, elemental cycles and renewable biofuels for energy, among others. New initiatives and collaborations are addressing prospects for limiting the effects of global change and maintaining a sustainable biosphere by managing microbial activities at local to global scales. For example, a recent program sponsored by National Science Foundation and the National Institutes of Health promises new understanding about the ecology of infectious and emerging diseases and linkages to climate change. These and other global change programs should be strengthened and expanded.

For much of its history, Earth was a planet of microbes. Even today, microbes dominate the living world in terms of biomass and numbers. Although human activity has altered many features of the Earth directly, significant changes on the land and in the oceans and atmosphere have also occurred indirectly through the impact of humans on microbes. Limiting the scope of future changes will require significant and sustained research on the complex interactions among humans, microbes and the Earth's physical and chemical systems.

Developing and Implementing New Solutions for Global Change Problems

Microbiological solutions to the challenges of global change will only be possible with greater understanding of how and why microbes (and microbial diversity) affect the behavior and complexity of macroorganisms and their environments at regional to global scales. This necessitates a national effort to strengthen and expand ongoing research and to direct new resources for basic research programs. The magnitude of potential problems associated with global changes demands a broad and aggressive, multidisciplinary scientific response, which must include extensive microbiological research and greater participation by microbial ecologists in the development of the basic knowledge that is essential for informed policy development, regulation and decision-making related to human-environment interactions.

Recommendations for Action

To enhance microbiological solutions to global change challenges, strengthen and expand ongoing research efforts, and direct new resources for basic research programs that:

1. *Integrate an understanding of microbiological processes at all organizational levels, from individual organisms to ecosystems, with the goals of:*
   - Improving carbon management (e.g., reducing net anthropogenic CO_2 emission to the atmosphere by increasing carbon storage in the biosphere)
   - Improving understanding of the budgets and controls of trace gases active in climate and atmospheric chemistry (e.g., Methane, Nitrous Oxide, Nitrogen Oxide, Dimethyl sulfide, Carbon Monoxcide), and options for minimizing anthropogenic disturbances of these gases
   - Improving understanding of the mobilization and toxicity of metals and related elements (e.g., copper, zinc, mercury, selenium, arsenic), and use of microbes for minimizing the effects of anthropogenic disturbances
   - Improving management of eutrophication at regional to global scales, with particular emphasis on groundwaters and coastal ecosystems.
2. *Discover, characterize and harness the abilities of microbes that play important roles in transformations of trace gases and various toxic elements.*

Implement policies that promote effective long-term research on the microbiology of global change by:

1. *Establishing research programs that are:*
   - Multidisciplinary, drawing on microbiology as a whole and on partner disciplines (e.g., soil science, climatology, geology, geochemistry, ecology, oceanography and molecular biology)
   - Mechanistic in their approach, seeking understanding at a basic level that will provide knowledge necessary for predicting responses of microbes to a globally changing environment
   - Sustained in duration (more than three to five years) to realize the benefits of multidisciplinary approaches
   - Multi-agency, incorporating all Federal agencies charged with understanding or managing the environment
2. *Establish programs to train people to solve tomorrow's complex environmental problems by:*
   - Directing additional resources to undergraduate and graduate multidisciplinary training in microbial ecology, atmospheric chemistry, biogeochemistry, and ecosystem science.
   - Improving the knowledge of K-12 students and instructors in microbiology and global change.

References

Branfireun, B.A., N.T. Roulet, C.A. Kelly, and J.W.M. Rudd. 1999. In situ sulphate stimulation of mercury methylation in a boreal peatland: toward a link between acid rain and methylmercury contamination in remote environments. Global Biogeochem. Cyc. 13:743-750.

Chappellaz, J., J.M. Barnola, D. Raynaud, Y.S. Korotkevich, and C. Lorius. 1990. Ice-core record of atmospheric methane over the past 160,000 years. Nature (Lond.) 345:127-131.

Colwell, R.R. 1996. Global climate and infectious disease: the cholera paradigm. Science 274:2025-2031.

Fenchel, T., G.M. King and T.H. Blackburn. 1998. Bacterial biogeochemistry: an ecophysiological analysis of mineral cycling. Academic Press, New York. 307 p.

Fuhrman, J.A. 1999. Marine viruses and their biogeochemical and ecological effects. Nature (Lond.) 399:541-548.

Galloway, J.N., W.H. Schlesinger, H. Levy, II, A. Michaels, and J.L. Schnoor. 1995. Nitrogen fixation: anthropogenic enhancement-environmental response. Global Biogeochem. Cyc. 9:235-252.

Hansen, J., M. Sato, R. Ruedy, A. Lacis, and V. Oinas. 2000. Global warming in the twenty-first century: an alternative scenario. Proc. Natl. Acad. Sci. (USA)

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D.M.E. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith, and G.R. Vasta. 1999. Emerging marine diseases—climate links and anthropogenic factors. Science 285:1505-1510.

Justic, D., N.N. Rabalais, and R.E. Turner. 1996. Effects of climate change on hypoxia in coastal waters: a doubled CO_2 scenario for the northern Gulf of Mexico. Limnol. Oceanogr. 41:992-1003.

King, G.M. 1997. Responses of atmospheric methane consumption by soils to global climate change. Glob. Change Biol. 3:351-362.

Linthicum, K.J., A. Anyamba, C.J. Tucker, P.W. Kelley, M.F. Myers, C.J. Peters. 1999. Climate and satellite indicators to forecast Rift Valley Fever epidemics in Kenya. Science 285:397-397-400.

Matthews, E. 1994. Nitrogenous fertilizers: global distribution of consumption and associated emissions of nitrous oxide and ammonia. Global Biogeochem. Cyc. 8:411-439.

Oechel, W.C., S.J. Hastings, M. Jenkins, G. Reichers, N. Grulke and G. Vourlitis. 1993. Recent change of arctic tundra ecosystems from a net carbon sink to a source. Nature 361:520-526.

Oremland, R.S. (editor). 1993. Biogeochemistry of global change: radiatively active trace gases. Academic Press, New York.

Paerl, H.W. 1997. Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnol. Oceanogr. 42:1154-1165.

Rabalais, N.N., R.E. Turner, Q. Dortch, W.J. Wiseman, Jr., and B.K. Sen Gupta. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19:386-407.

Schlesinger, W.H. 1997. Biogeochemistry: an analysis of global change. Academic Press, San Diego.

Strous, M., J.A. Fuerst, E.H.M. Kramer, S. Logemann, G. Muyzer, K.T. van de Pas-Schoonen, R. Webb, J.G. Kuenen and M.S.M. Jetten. 1999. Missing lithotroph identified as new planctomycete. Nature (Lond.) 400:446-449.

Whitman, W.B., D.C. Coleman, and W.J. Wiebe. 1998. Prokaryotes: the unseen majority. Proc. Natl. Acad. Sci. USA 95:6578-6583.