Biogeochemical Cycles
Microbial Influence
Microbial Contributions
Global Environmental Change

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Tony Greene- Mol Appl Microbiol

Microbial Contributions to The Earths Atmosphere

1. Microbes are responsible for cycling life essential elements (O_2, N_2, C, S, and H_2):

a. The sheer number of microbes on Earth is staggering:
5 × 1031 microbes (50 quadrillion metric tons)
= ~90% of the earth's biomass, excluding cellulose
= >60% of the biomass including cellulose

b. Producers of O_2: The basic chemistry of Earth's surface[1] is determined by biological activity- photosynthesis. Microbes (cyamobacteria & algae carry out more photosynthesis plants; aerobic & anaerobic = major O_2 microbially derived)

c. Transformers of N_2: Required for proteins, NAs & other cellular components. 80% atmosphere is N_2 but this gas is unavailable for use by most organisms. The strong bonds between the two atoms of N_2 renders it almost inert. In order for the N_2 to be useful for growth, it must first be combined or "fixed". N_2 → NH_3 (N_2 fixation-symbiosis or free-living); NH_3 to NO_3; decompose organic matter, releasing fixed N_2 (denitrification).

[1] The deep ocean bioactivity is chemolithotrophic–discussed earlier. See also URL http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/oceanography_recently_revealed1.html

Microbial Ecology- Part II. Global Biogeochemical Cycles

Metabolism, physiology, nutrient cycling and environmental adaptation

The earth is a closed system with limited amounts of carbon, oxygen and nitrogen available to all forms of life. These essential elements must be converted from one form to another and shared among all living organisms. The most significant effect that microbes have on their environment is their ability to recycle the essential elements that make up cells. The redox cycling of elements (C, N & S) catalysed to varying degrees by microbes (biotransformation) at a global scale (transfer of elements from one place to another).

Table 1 lists the major elements that make up a typical procaryotic cell such as *E. coli*. Over 90 percent consists of C, H, O, N, P and S. These elements are the constituents of organic material and combine to form all the biochemicals that comprise living systems. C, H, O, N, P and S. Organic compounds on earth are evidence of life. The empirical formula for organic compounds is $(CH_2O)_n$ where H and O are the constituents of water (H_2O), and makes up > 95% of the cell composition. Inorganic salts in cellar cytoplasm include calcium (Ca^{++}), iron (Fe^{++}), magnesium (Mg^{++}) and potassium (K^+).

Table 1. Major elements, their sources and functions in cells.

Element	% of dry weight	Source	Function
Carbon	50	Organic compounds or CO_2	Main constituent of cellular material
Oxygen	20	H_2O, organic compounds, CO_2, and O_2	Constituent of cell material and cell water; O_2 is electron acceptor in aerobic respiration
Nitrogen	14	NH_3, NO_3, organic compounds, N_2	Constituent of amino acids, nucleic acids nucleotides, and coenzymes
Hydrogen	8	H_2O, organic compounds, H_2	Main constituent of organic compounds and cell water
Phosphorus	3	inorganic phosphates (PO_4)	Constituent of nucleic acids, nucleotides, phospholipids, LPS, teichoic acids
Sulfur	1	SO_4, H_2S, S, organic sulfur compounds	Constituent of cysteine, methionine, glutathione, several coenzymes
Potassium	1	Potassium salts	Main cellular inorganic cation and cofactor for certain enzymes
Magnesium	0.5	Magnesium salts	Inorganic cellular cation, cofactor for certain enzymatic reactions
Calcium	0.5	Calcium salts	Inorganic cellular cation, cofactor for certain enzymes and a component of endospores
Iron	0.2	Iron salts	Component of cytochromes and certain nonheme iron-proteins and a cofactor for some enzymatic reactions

Note: Trace elements which are metal ions required in cellular nutrition in such small amounts that it is difficult to determine their presence in cells and are therefore ignored in the table. The usual trace elements are Mn^{++}, Co^{++}, Zn^{++}, Cu^{++} and Mo^{++}. Trace elements are usually built into vitamins and enzymes. For example, vitamin B_{12} contains cobalt (Co^{++}) and the bacterial nitrogenase enzyme contains molybdenum (Mo^{++}).

The structure and metabolism of any organism adapts it to its environment. Thus the various groups of microbes are adapted to certain environmental niches based on their predominant type of metabolism relevant to the elemental nutrients available.

The **fungi** (molds and yeasts)- aerobes that utilize organic compounds for growth and play an important role in decomposition (biodegradation) of organic matter, particularly in soil (carbon cycle). Yeasts can grow anaerobially (without oxygen) through the process of fermentation and play a role in fermentations in environments high in sugar.

The **algae**- a predominant photosyntheic eucaryotic produces in many aquatic environments. They are **autotrophs-** use atmospheric carbon dioxide (CO_2) as a source of carbon for growth and convert it into algal cellular organic material- similar to plants (important in carbon cycle). The **cyanobacteria** are a group of procaryotic microbes, and are as prevalent as algae and make a very large contribution to the carbon and oxygen cycles. They are a major component of marine plankton and are the basis of the food chain in the oceans.

Protozoans are heterotrophic organisms that have to catch or trap their own food- developed elaborate mechanisms for movement and acquiring organic food which they can digest. Their food usually turns out to be bacterial cells, so one might argue that they are ecological predators that keep bacterial populations under control.....in soil, aquatic environments, intestinal tracts of animals, and many other environments.

The procaryotic ***Bacteria*** and ***Archaea***, as a result of their diversity and unique types of metabolism, are involved in the cycles of virtually all essential elements. In two cases, methanogenesis (conversion of carbon dioxide into methane) and nitrogen fixation (conversion of nitrogen in the atmosphere into biological nitrogen) are unique to procaryotes and earns them their "essential role" in the carbon and nitrogen cycles.

There are other metabolic processes that are unique, or nearly so, in the procaryotes that bear significantly on the cycles of elements. For example, procaryotes called **lithotrophs** use inorganic compounds like ammonia and hydrogen sulfide as a source of energy, and others called **anaerobic respirers** use nitrate (NO_3) or sulfate (SO_4) in the place of oxygen, so they can respire without air. Most of the archaea are lithotrophs that use hydrogen (H_2) or hydrogen sulfide (H_2S) as a source of energy, while many soil bacteria are anaerobic respirers that can use their efficient respiratory metabolism in the absence of O_2.

The basic processes of heterotrophy are spread throughout the bacteria. Most of the bacteria in the soil and water, and in associations with animals and plants, are heterotrophs. **Heterotrophy** means living off of dead organic matter, usually by some means of respiration (same as animals) or fermentation (same as yeast or lactic acid bacteria). Bacterial heterotrophs in the carbon chain are important in the processes of biodegradation and decomposition under aerobic and anaerobic conditions.

In bacteria, there is a unique type of photosynthesis that does not use H_2O or produce O_2 which impacts on the carbon and sulfur cycles.

The list of examples of microbial involvement in the cycles of elements that make up living systems is endless, and probably every microbe in the web is involved in an intimate and unique way.

What is biogeochemical cycling?

The earth is a closed system with limited amounts of carbon, oxygen and nitrogen available to all forms of life. These essential elements must be converted from one form to another and shared among all living organisms. The most significant effect that microbes have on their environment is their ability to recycle the essential elements that make up cells. The redox cycling of elements (C, N & S) catalysed to varying degrees by microbes (biotransformation) at a global scale (transfer of elements from one place to another).

Why is it important to study biogeochemical cycles?

Calculations on biotransformations give an indication of human disturbances to the biogeochemical cylces (eg methane generation in rice paddy fields).

How are the biogeochemical cycles studied?

Biotransformation calculations can be achieved by dividing the earth into a series of compartments:

- atmosphere

- land

- ocean (water and sediments)

- Earth's crust (surface)

Each compartment is a reservoir within which an element is stored for a definite period of time.

The movement of elements within the compartment varies; rapid (atmosphere) or slow (ocean sediments). In case of ocean sediments, the elements may be converted into sedimentary rocks which can reach the surface of the earth when tectonic forces causes uplift and mountain building. The mountains weather over time and by soil erosion are transferred and deposited in ocean sediments and remain for many millions of years.

The movement of element from one compartment to another is known as FLUX. The length of time an element remains in a compartment is expressed as its residence time. Some elements have short residence time whereas others have long residence times.

The oxygen cycle:

O_2 is derived from the photolysis of H_2O during **plant (oxygenic) photosynthesis.** Two major groups of microorganisms are involved in this process- the eukaryotic algae, and the procaryotic cyanobacteria (also referred to as blue-green algae). The cyanobacteria and algae predominate marine habitats which covers the majority of the planet and hence are the sources of much of the O_2 in the earth's atmosphere. Plants account for only some O_2 production.

Since most aerobic organisms need the O_2 that results from plant photosynthesis, this establishes a relationship between plant photosyntheisis and aerobic respiration, two prominant types of metabolism on earth. Photosynthesis produces O_2 needed for aerobic respiration. Respiration produces CO_2 needed for autotrophic growth.

$CO_2 + H_2O$-----------------> CH_2O (organic material) + O_2 plant (oxygenic) photosynthesis

$CH_2O + O_2$-----------------> $CO_2 + H_2O$ aerobic respiration

Since these photosynthetic microbes are also autotrophic (meaning they convert CO_2 to organic material during growth) they have a similar impact on the carbon cycle (below).

The carbon cycle:

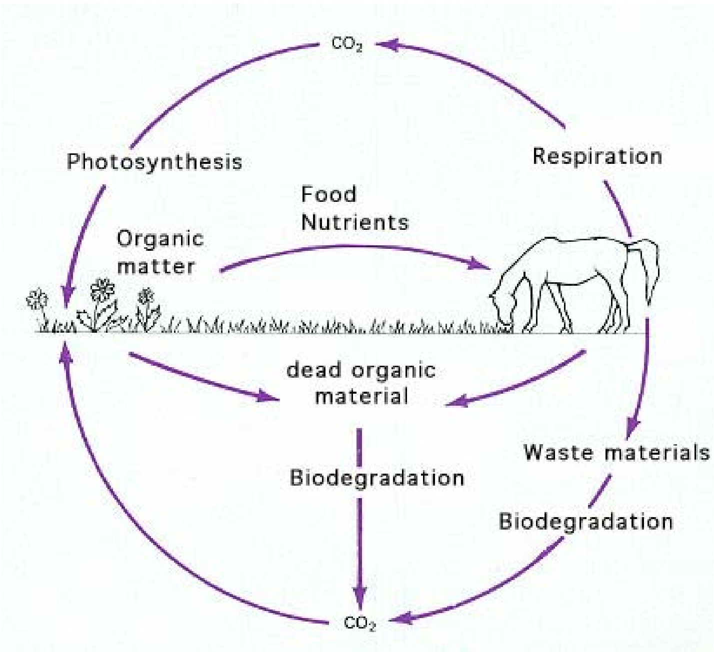
The carbon cycle is a central biogeochemical cycle as life is based on the carbon atom. Other cycles are driven by energy derived from photosynthesis or the breakdown of organic compounds.

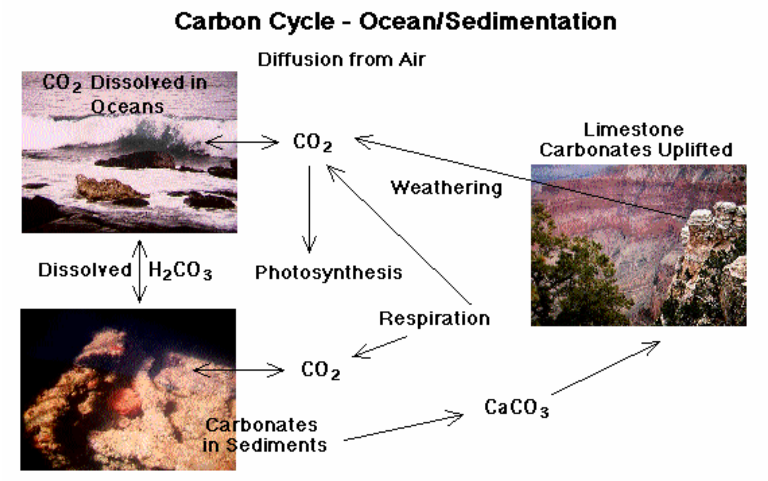
Carbon exists in 3 oxidation states:

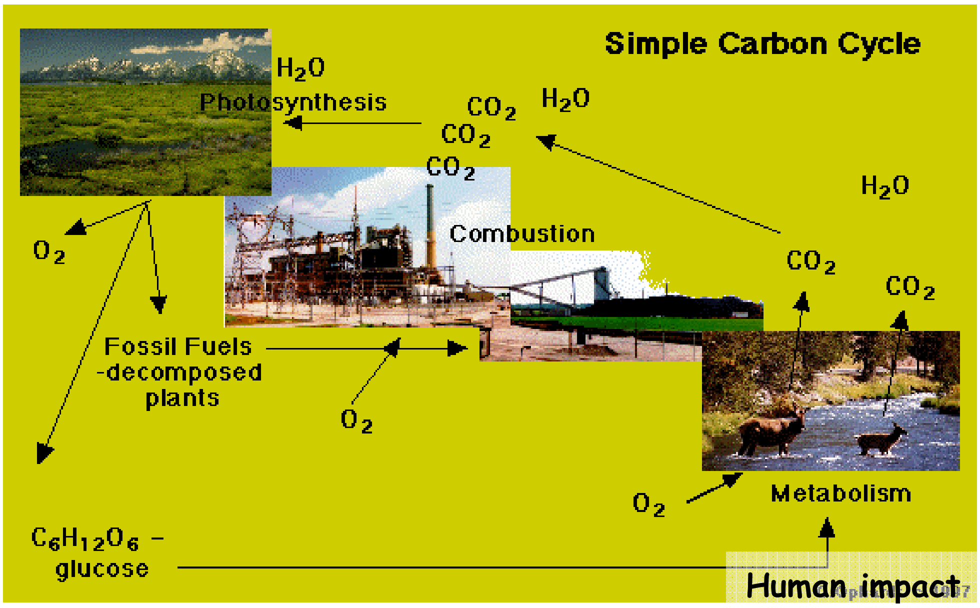
- CH_4 - the most reduced.
- $(CH_2O)_n$ - a general formula for protoplasm, oxidation state equivalent to the carbohydrate
- CO_2 - the most oxidized

The residence time of carbon is different compartments is very different and depends on carbon availabilty and how it is fluxed.

Complex organic compounds are primarily derived from the incorporation of CO_2 aerobically by plants or anaerobically by microbal phototrophs. These complex organic compounds are than degraded anaerobically (eg fermentation) or aerobically (respiration eg breathing). The figure provides an overview of the process







The Nitrogen Cycle:

N_2 constitutes 75 - 79% of earth's atmosphere

Two nitrogen oxides are found in the air as a result of interactions with oxygen. Nitrogen will only react with oxygen in the presence of high temperatures and pressures found near lightning bolts and in combustion reactions in power plants or internal combustion engines. Nitric oxide (NO) and nitrogen dioxide (NO_2) are formed under these conditions. Eventually nitrogen dioxide may react with water in rain to form nitric acid, HNO_3. The nitrates thus formed may be utilized by plants as a nutrient.

Nitrogen containing molecules include amino acids, nucleic acids, and nitrogen containing biological molecules.

There are 4 main steps involved in making atmospheric nitrogen available to living organisms and than returning nitrogen back to the atmosphere as shown in the figure and include:

- (a) Nitrogen fixation (growth aerobic, fixation anaerobic)

- (b) Ammonification (aerobic or anaerobic)

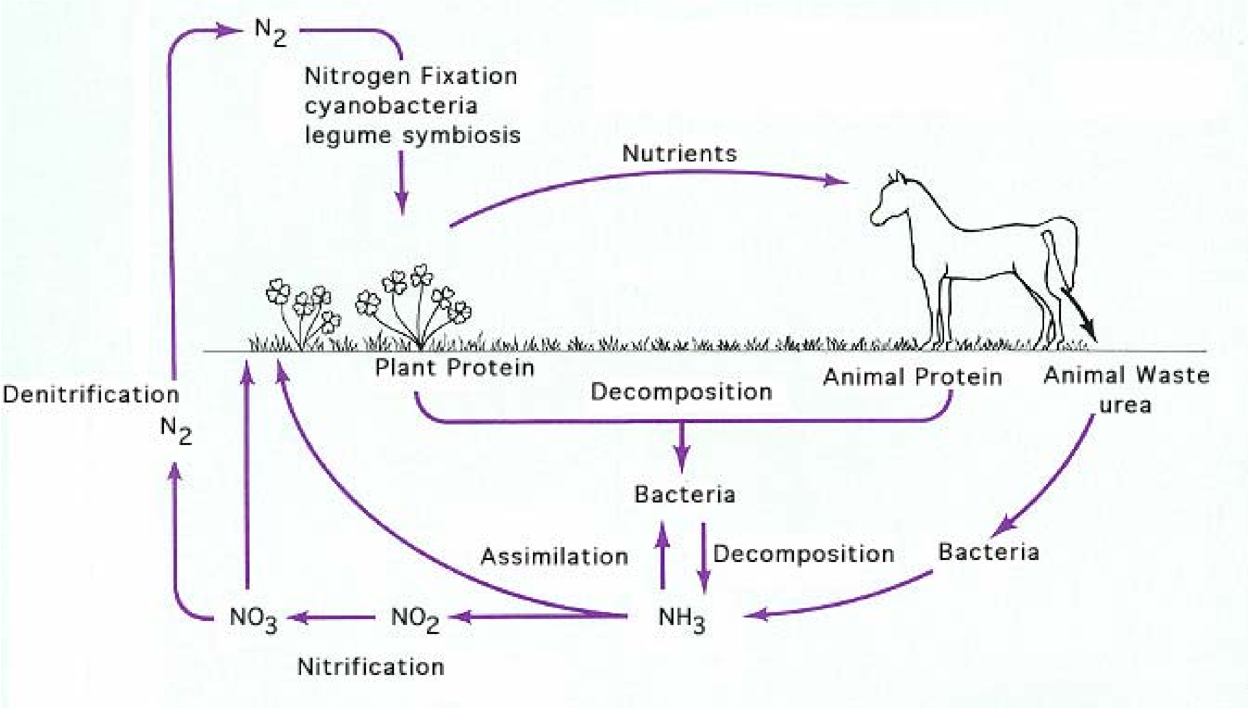
- (c)Nitrification (aerobic)

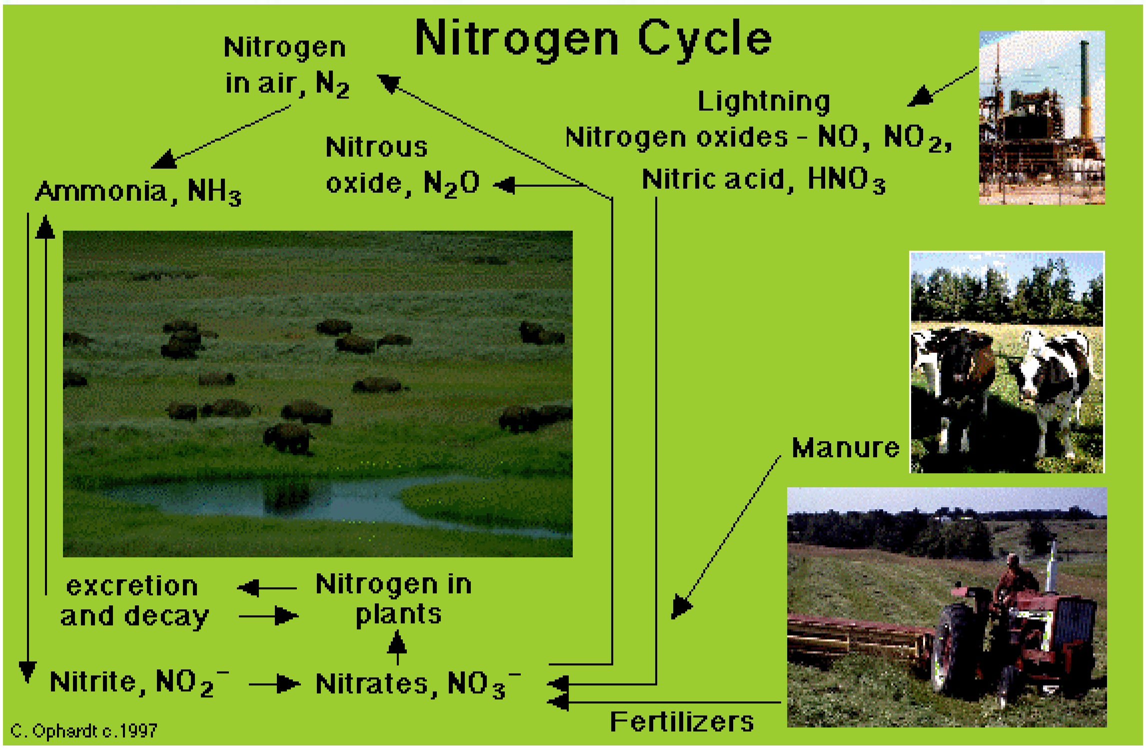
- (d) Denitrification (anaerobic)

N_2 has 3 bonds making it very stable and energy is required to break the bonds. The nitrogen in the air becomes a part of biological matter mostly through the actions of bacteria and algae in a process known as **nitrogen fixation**. Legume plants such as clover, alfalfa, and soybeans form nodules on the roots where nitrogen fixing bacteria take nitrogen from the air and convert it into ammonia, NH_3. The ammonia is further converted by other bacteria first into nitrite ions, NO_2^-, and then into nitrate ions, NO_3^-. Plants utilize the nitrate ions as a nutrient or fertilizer for growth. Nitrogen is incorporate in many amino acids which are further reacted to make proteins.

Ammonia is also made through a synthetic process called the Haber Process. Nitrogen and hydrogen are reacted under great pressure and temperature in the presence of a catalyst to make ammonia. Ammonia may be directly applied to farm fields as fertilizer. Ammonia may be further processed with oxygen to make nitric acid. The reaction of ammonia and nitric acid produces ammonium nitrate which may then be used as a fertilizer. Animal wastes when decomposed also return to the earth as nitrates.

To complete the cycle other bacteria in the soil carry out a process known as denitrification which converts nitrates back to nitrogen gas. A side product of this reaction is the production of a gas known as nitrous oxide, N_2O. Nitrous oxide, also known as "laughing gas" - mild anesthetic, is also a greenhouse gas which contributes to global warming





(a) Nitrogen fixation:

Nitrogen fixing bacteria include

- *Azotobacter*, some *Bacillus*, *Klebsiella*, *Rhodospirllum* (photosynthetic) and *Anabaena*, *Nostoc* (cyanobacteria, blue-green algae) fix N_2 directly- free-living N_2 fixers

- *Rhizobium*, *Spirillum*, *Frankia alni* are symbiotic N_2 fixers with specific hosts viz roots of leguminous plants, tropical grasses and alder trees

Symbiotic and free-living fixation requires nitrogenase enzyme and the following reaction occurs:

Nitrogen + nitrogenase ------> 2 molecules of ammonia ------> incorporation into amino acid

- *Azotobacter* - heterotrophs; more carbon means more fixation

- *Rhodospirillum* - phototroph; light dependent fixation

- *Rhizobium* - host specific fixation

Nitrogen fixation occurs under anaerobic conditions only & nitrogenase enzyme has to be protected from oxygen:

- leghemoglobin (synthesised jointly by *Rhizobium* and the plant) - binds 0_2

- heterocysts - protective compartment in cyanobacteria

- cysts (membranous structure) - *Azotobacter*

- Fixation only if anaerobic conditions present - *Klebsiella*

Two approaches to increase N_2 fixation:

- Genetic approach: Introduce nitrogen fixing genes (nif genes) into non- N_2 fixing plants (eg corn, wheat which provide good carbohydrates); Problems include protecting nitrogenase from 0_2 and energy required for fixation will be used from the plant at the expense of plant growth.

- Microbial ecology: Isolation of new strains of N_2 fixers (increase biodiversity)and establish new symbiotic relationships or new associations between plants and N_2 fixing bacteria.

(b) Ammonification:

Fixed nitrogen that is locked up in the protoplasm (organic nitrogen) of N_2 fixing microbes has to be released for other cells. This is done by the process of ammonification with the assistance of deaminating enzymes.

Alanine + deaminating enzyme --------> ammonia + pyruvic acid

It is ammonia rather than the organic nitrogen that is required by most plants and hence the role of microbes in the process is extremely important.

(c) Nitrification:

The most widely used inorganic nitrogen source for plant and animal growth is nitrate.

The production of inorganic nitrate is a 2 stage process:

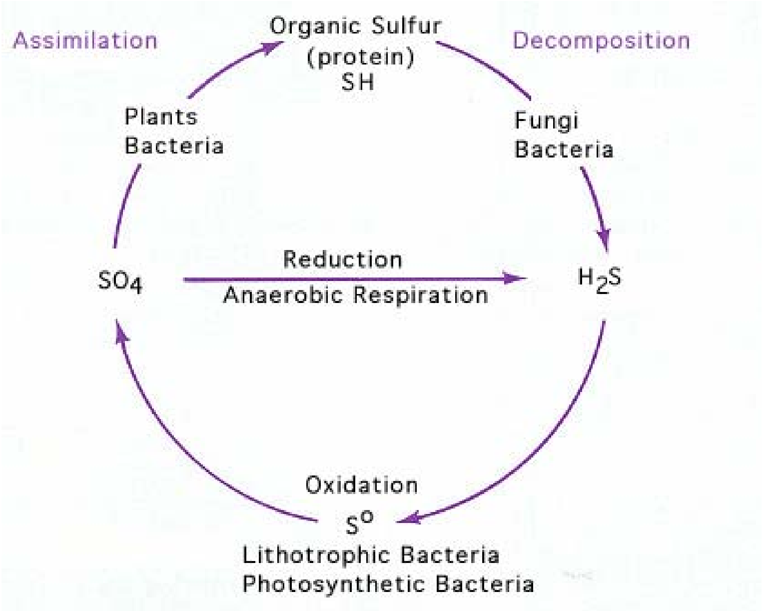
- NH_4^+ ------> NO_2 (partial oxidation of NH_4^+): eg *Nitrosomonas*; chemolithotrophs obtain energy by aerobic oxidation of inorganic compounds and cell carbon by CO_2 fixation

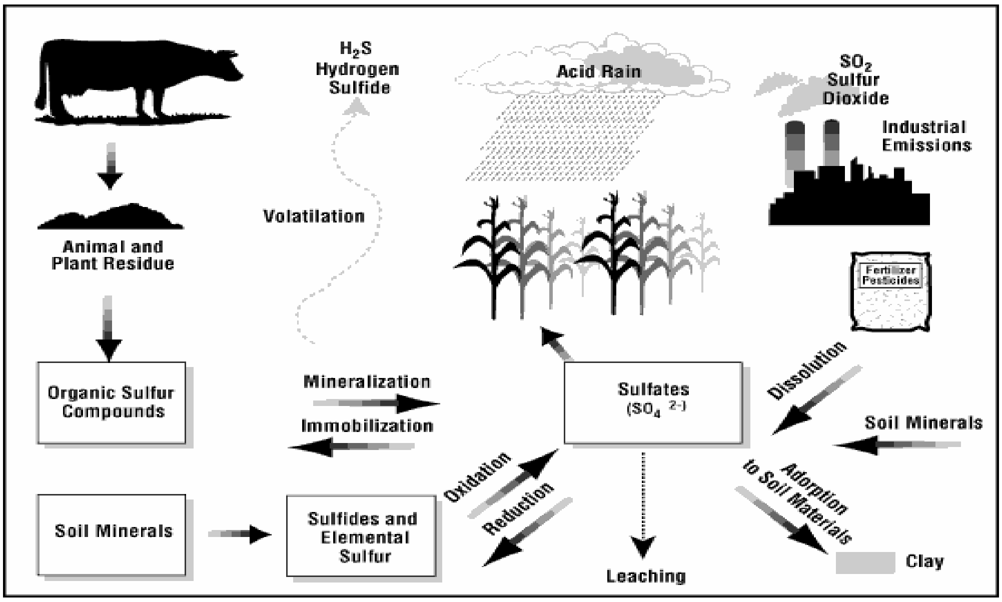
- NO_2 ------> NO_3 eg *Nitrobacter*

(d) Denitrification:

NO_3 is a +5 oxidation state ie highest state possible and returns to 0 (zero) state by denitrification process which is a sequential addition of electrons to NO_3 to produce N_2

The sulfur cycle:





There are 4 chemical forms of sulfur:

- Elemental sulfur (S^o): oxidation state of 0

- Sulfide (H_2S, FeS): oxidation state of -2

- Organic mercaptans, aminoacids (meth, cyst): oxidation state of -2

- Sulfate (H_2S0_4): oxidation state of +6

All transformations are microbially mediated

All transformations depend on the oxygen content in the environment

- S^o in aerated environments ----------> $S0_4$

- S^o in anaerobic environments -------> H_2S

Begin looking at the sulfur cycle from the organic sulfur (eg meth, cyst, certain vitamins) from dead organisms which decompose by microbial enzymes in the release of H_2S.

The H_2S release is either:

- released into the environment OR

- reacts with metals to form FeS (ferrous sulfide)

H_2S and FeS are in their most reduced oxidation state and are oxidised to SO_4; Two different metabolic pathways operate in microbes for oxidation

- Two stepped process in which H_2S and FeS are oxidised to elemental S^o first (intracellular eg phototrophic *Chromatium*; or extracellular eg *Ectothiorhodospira*, *Chlorobium*) and than to SO_4

- In *Thiobacillus*, H_2S and FeS are oxidised to cellular sulfhydryl organic compounds, than to sulfides and finally to SO_4

The SO_4 that is produced reacts with water to form H_2SO_4. Thiobacillus thiooxidans produces huge amounts of sulfuric acid; an acidophile (optimum pH for growth = 2.0 to 3.5).

- Advantage: Alkaline soils can be turned into acidic soils by addition of *T. thiooxidans* and S^o

- Disadvantage: Causes pollution eg pyrite oxidation in coal mines

Finally, SO_4 can be used as an electron acceptor and reduced to H_2S by sulfate reducing bacteria (SRB), a physiologically cohesive anaerobic microbial group. The group is involved in biocorrosion of metals, the H_2S produced is extremely toxic ad is known to kill total fish populations of organically rich (polluted) lakes

Global Environmental Change

Microbial Contributions
Microbial Solutions

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MICROBIOLOGY

- The O_2 we inhale- so vital to our existence.
- CO_2, CH_4 & nitrous oxide are important atmospheric gases- elevated concentrations contribute to global warming.
- To understand global change & warming and to find solutions for undesirable changes we must explore the past history of earth, it's atmosphere, origin of life & biological evolution (the early part was exclusively microbial) http://www.pbs.org/wgbh/evolution/change/deeptime/index.html[1]

[1] There are a number of other fascinating essays on evolution at the URL http://www.pbs.org/wgbh/evolution/library/03/index.html

Summarising the evolution of the Earth's atmosphere:

The history of the very early Earth's atmosphere is poorly understood, but a plausible sequence of events is as follows:

- Original primary atmosphere- helium and hydrogen; heat (from the still-molten crust, and the sun) dissipated this atmosphere & ~ 3.5 billion years ago, a surface crust formed due to cooling, but still heavily populated with steam, CO_2, and NH_3 releasing volcanoes.

- Second atmosphere- primarily CO_2 and water vapour, with some N_2 (no O_2); however 2005 experiments suggests 40% H_2 was also present. This second atmosphere had approximately 100 times as much gas than today. It is generally believed that the greenhouse effect, caused by high levels of CO_2, kept the Earth from freezing.

- Third atmosphere (the modern earth's O_2-N_2 atmosphere) - During the next few billion years, water vapour condensed to form rain and oceans, which began to dissolve CO_2. Approximately 50% of the CO_2 would be absorbed into the oceans. One of the earliest types of bacteria were the cyanobacteria. Fossil evidence indicates that these bacteria existed approximately 3.3 billion years ago and were the first O_2 -producing evolving phototropic organisms. They were responsible for the initial conversion of the earth's atmosphere from an anoxic state to an oxic state. Being the first to carry out oxygenic photosynthesis, they were able to convert CO_2 to O_2

- Photosynthesizing plants would later evolve and convert more CO_2 to O_2. Over time, excess carbon became locked in fossil fuels, sedimentary rocks (notably limestone), and animal shells. As oxygen was released, it reacted with ammonia to create nitrogen; in addition, bacteria would also convert ammonia into nitrogen.

- As more plants appeared, the levels of oxygen increased significantly, while carbon dioxide levels dropped. At first the oxygen combined with various elements (such as iron), but eventually oxygen accumulated in the atmosphere, resulting in mass extinctions and further evolution. With the appearance of an ozone layer (ozone is an allotrope of oxygen) lifeforms were better protected from ultraviolet radiation. This oxygen-nitrogen atmosphere is the "third atmosphere".

The oxygen requirement by different tissues / organs is different and in some cases, eg brine shrimp & the neamtode *C. elegans* can survive without O_2- you can ead more on this at the URL

http://scienceweek.com/2005/sw051216-3.htm and http://www.safar.pitt.edu/content/grant/jc/2005/0325%20Wu%201.pdf.

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.

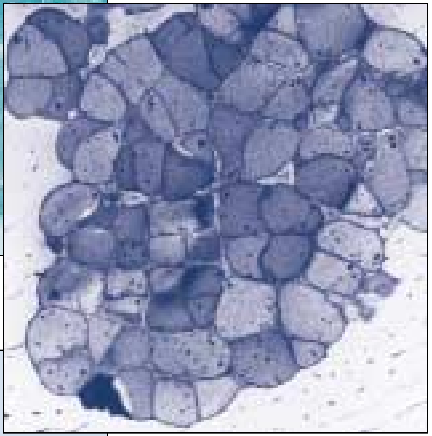
Banded Iron Formation. Microbes have produced rich metal deposits within the Earth's Crust.

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)

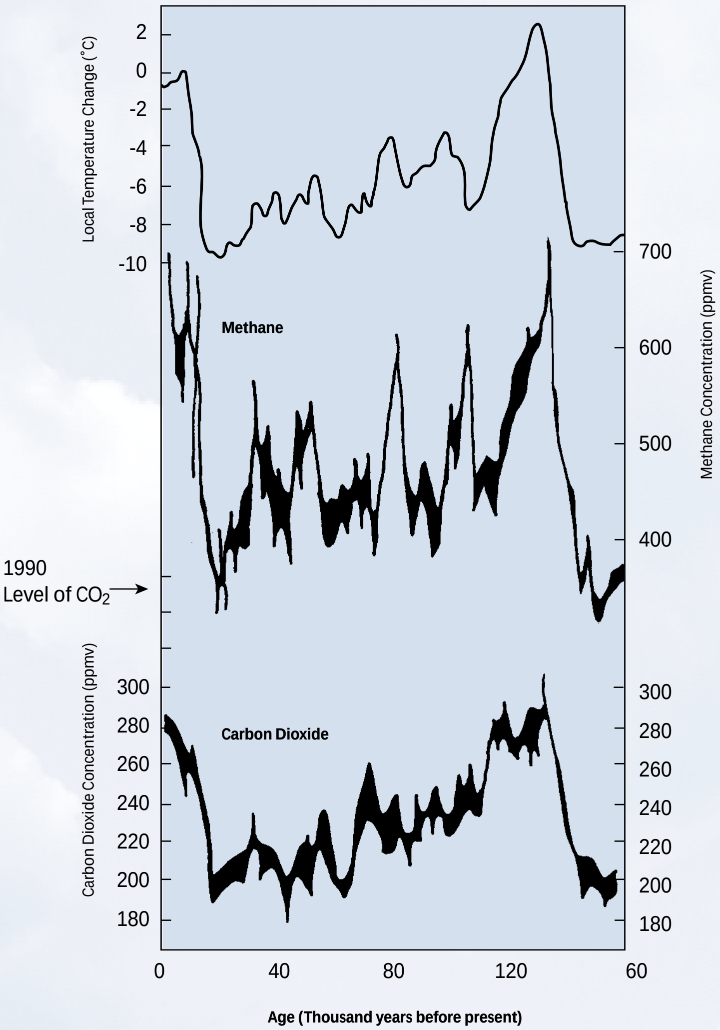
Biological Contributions to Atmospheric Composition

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

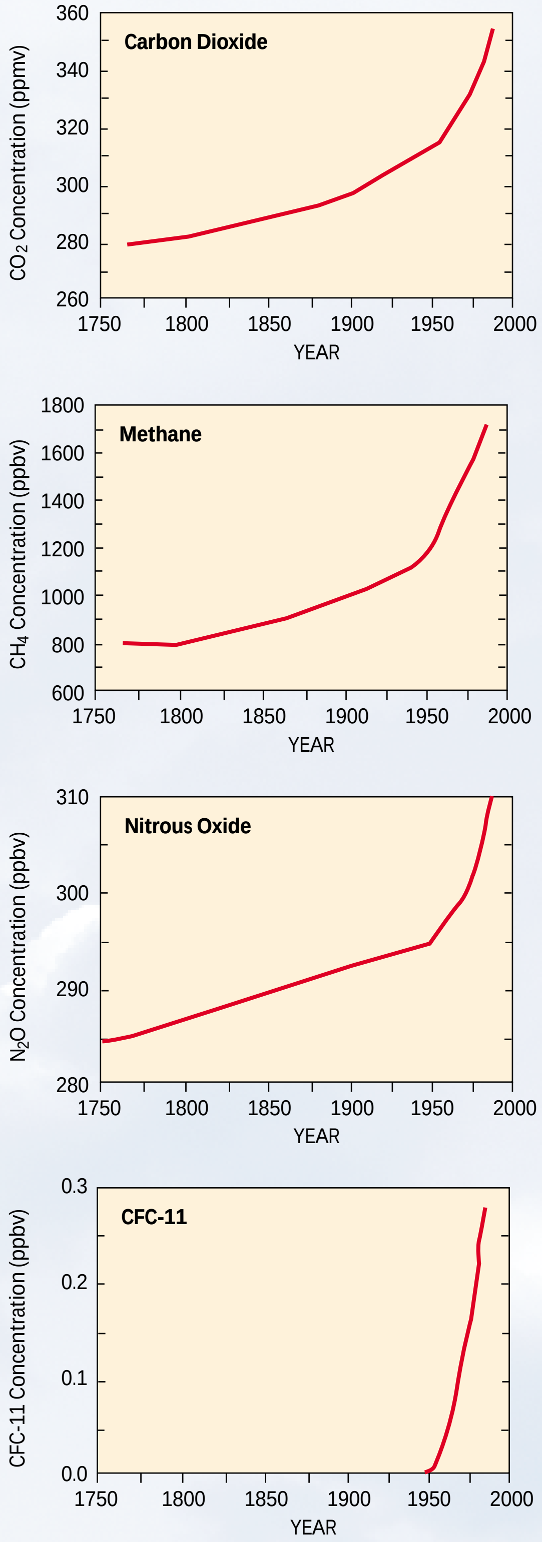
Gases trapped in Antarctic ice reveal natural changes in atmospheric composition coincident with changes in climate. Carbon dioxide (CO_2) and methane concentrations rise during warm periods and decrease during colder periods.



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.

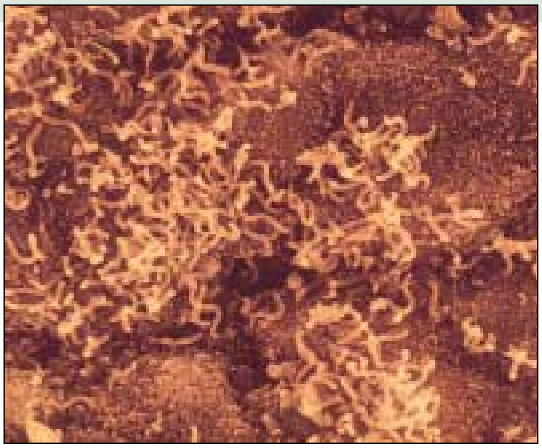
Contemporary Changes in Atmospheric Trace Gases

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



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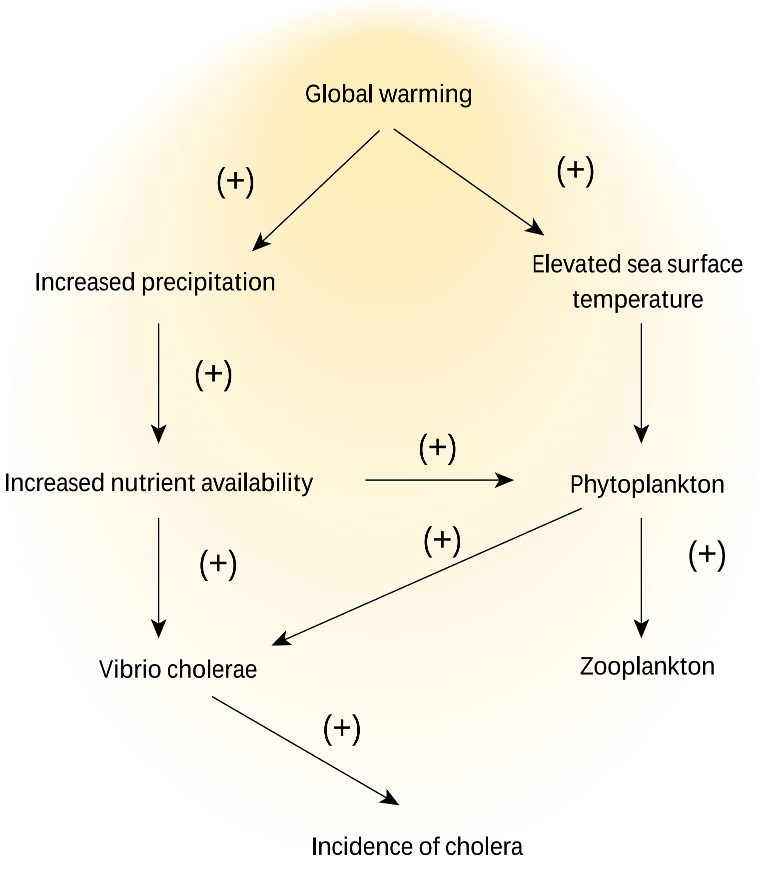
V. cholerae. The distributions and health threats of many disease-causing organisms, such as the agent for cholera, are linked to climate.

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.

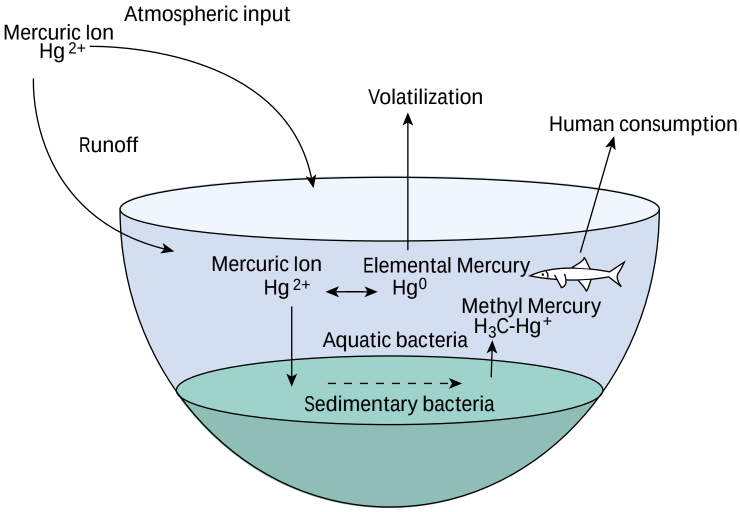
Relationship between sea-surface temperature (SST) and cholera case data in Bangladesh from January to December 1994.

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.



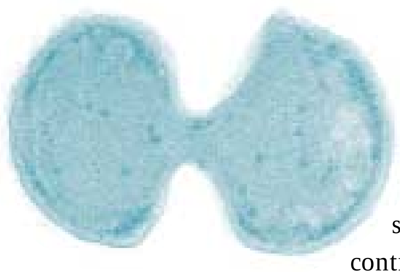
Aquatic Mercury Cycling. Bacteria in the water column and sediments transform mercury from natural and anthropogenic sources into forms that can be further mobilized or enter food chains resulting in severe impacts on animal and human health.

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.