**Module Essay 1**

Generally, the community of microbiology experts have reached the consensus that humans would not be able to live without microbes. Falkowski et al.(1) commented that “*Microbial life can easily live without us; we, however, cannot survive without the global catalysis and environmental transformations it provides.".* It may be bold to assume they are necessary for our survival, but their existence is essential to our current lifestyle. Microbial networks facilitate the biogeochemical processes that cycle our nutrients and maintain a livable atmosphere. They are difficult to replicate because of their complexity and scale, and efforts to emulate them have resulted in environmental damage. Furthermore, their resilience makes them valuable assets in our fight against climate change.

Microbes form metabolic networks that facilitate the biogeochemical processes which fix and cycle our nutrients. Carbon and nitrogen are necessary for the production of biological building blocks that make up our body (2), but they cannot be utilized as our nutrients unless they are either converted from its inorganic form or reduced. Nitrogen can only be incorporated into biological molecules through nitrogen fixation, where nitrogen gas (N2) is reduced to ammonium. Microbes are the only organisms that can accomplish this biotically, since their genes encode the enzyme nitrogenase—a heterodimeric complex that breaks apart the N≡N bond of N2 (1). Similarly, microbes are necessary for the movement of carbon between sinks. There are three times as many global organic carbon stocks stored in soil as the amount of inorganic carbon stored in the atmosphere as CO2 (3). If microbial respiration were to cease, current primary production would deplete atmospheric CO2 stocks in 12 years (4) and dramatically decrease the rate of photosynthesis in our crops.

The same metabolic networks are also crucial for maintaining a habitable atmosphere. They are responsible for almost all the oxygen we breathe (5). Both plants and microorganisms produce oxygen through photosynthesis, which is written as CO2 + H2O -> CH2O + O2. However, marine photosynthesis—carried out by microorganisms—produces the only net source of O2. Terrestrial respiration depletes the oxygen produced from terrestrial photosynthesis whereasa small percentage (0.1%) of the organic matter synthesized in the oceans is buried in sediments, preventing it from contributing to the reverse reaction (5). Without the marine photosynthesis executed by single-celled organisms such as diatoms and coccolithophorids, net production of O2 would cease and atmospheric O2 would gradually be exhausted through respiration (5).

We currently do not have the technological capacity to replace these metabolic networks due to their complexity and scale. Metabolic networks consist of individual redox reactions that are carried out by different macromolecular complexes that are encoded by many genes or housed in different microbial groups. In oxygenic photosynthesis, 100 genes alone are needed to encode the molecular complexes required for energy transduction (6). To further complicate matters, some pathways in biogeochemical cycles are catalyzed by diverse multispecies microbial interactions. In the nitrogen cycle, NH4+ is first oxidized to NO2- by a group of Bacteria or Archaea then a different group of nitrifying oxidizing bacteria oxidizes NO2- to NO3- (7). The scale of these reactions is another challenging aspect we would need to overcome. There are approximately prokaryotes on earth in total (8) and these numbers do not include eukaryotic microorganisms. The sheer abundance of these microorganisms demonstrates that these microbial metabolic networks exist at a large scale that we may never be able to reconstruct entirely.

Our attempts to emulate some of these metabolic networks have been damaging for the environment and further highlights our limitations. Humans have acquired the ability to fix nitrogen inorganically through fossil fuel combustion, almost doubling the rate of terrestrial nitrogen fixation. The excess NH4+ produced industriallyis converted to NO3- , which leaches into water reserves and creates anoxic zones. This lead to a rise in atmospheric N2O—a greenhouse gas that has 300 times global warming potential of CO2. These environmental damages are a testament of our inability to construct an elegant biochemical network like microbes. Until we can balance the inputs of our activities with an output that does not alter the climate, we will need to rely on the adaptive capabilities of microbes to produce a new steady state for the biosphere.

Microbes are invaluable allies in our efforts to combat climate change and our foray into the Anthropocene Era because of their resilience to environmental changes. We have disturbed major Earth-system processes through our interference with the nitrogen cycle and climate change, disturbing the very environmental conditions that enabled our development. To salvage the damage, we would require the help of microbes. They can adapt to environmental changes quickly because their large numbers and rapid growth gives them the capacity create genetically diverse groups—granting them the ability to form new metabolic networks. The formation of these new networks can create a new steady state where excess nitrogen or carbon dioxide is removed from the system at the same rate it is added (8). Indeed, up until the Industrial Revolution, the evolution and basic composition of Earth’s atmosphere was tightly linked to the evolution of their metabolic networks (5). Cyanobacteria, which are oxygen producers as well as major nitrogen fixers, have had to evolve complex mechanisms to protect their oxygen sensitive nitrogenase. Taken together, microbes’ ability to resist environmental changes through evolutionary processes make them indispensable allies in the fight against human-driven climate change.

If we are not careful, our intervention in microbial-driven biogeochemical processes can lead to irreversible changes.

1. Falkowski PG, Fenchel T, Delong EF. 2008. The microbial engines that drive earth’s biogeochemical cycles. Science (80- ) 320:1034–1039.

2. Schlesinger WH. 1997. Biogeochemistry: an analysis of global change -- 2nd ed. Acad Press San Diego 139–143.

3. Falkowski P, Scholes RJ, Boyle E, Canadell J, Canfield D, Elser J, Gruber N, Hibbard K, Hogberg P, Linder S, Mackenzie FT, Moore B, Pedersen T, Rosental Y, Seitzinger S, Smetacek V, Steffen W. 2000. The global carbon cycle: A test of our knowledge of earth as a system. Science (80- ) 290:291–296.

4. Sylvia DM, Fuhrmann JJ, Hartel PG, Zuberer DA, Cupples AM. 2005. Principles and applications of soil microbiologyJournal of Environment Quality.

5. Kasting JF, Siefert JL. 2002. Life and the evolution of earth â€TM s atmosphere. Library (Lond) 296:1066–1069.

6. Shi T, Bibby TS, Jiang L, Irwin AJ, Falkowski PG. 2005. Protein interactions limit the rate of evolution of photosynthetic genes in cyanobacteria. Mol Biol Evol 22:2179–2189.

7. Falkowski PG. 1997. Evolution of the nitrogen cycle and its influence on the biological sequestration of CO2 in the ocean. Nature 387:272–275.

8. Whitman WB, Coleman DC, Wiebe WJ. 1998. Prokaryotes: The unseen majority. Proc Natl Acad Sci 95:6578–6583.

9. Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley J. 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol Soc 14.