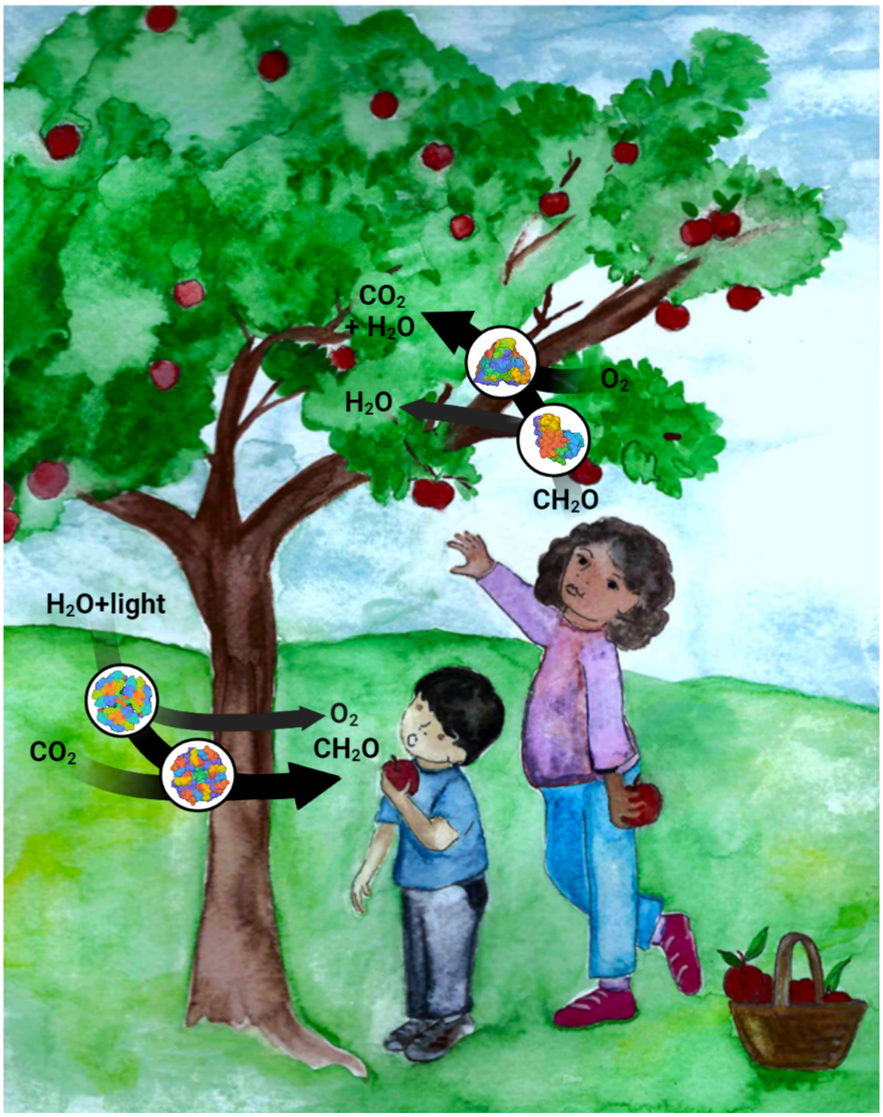
Protein nanomachines: how they helped create our planet

Do the plants in the park breathe air like me?



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Protein nanomachines

Storyline

All organisms exchange gases with the atmosphere. With each breath, our lungs fill with oxygen and expel carbon dioxide and water. This process produces energy from the food we eat. Where do we get the food? From plants, but plants do not have lungs like we do. Instead, they take in carbon dioxide and water through their leaves, and produce oxygen and sugars using the energy from sunlight. These sugars are then converted into the compounds that make up their stems, leaves, roots, and most of all their seeds and fruits. Plants and algae are photosynthetic. We are heterotrophs – organisms that use photosynthetic products for life. These two, fundamental processes, photosynthesis (left to right) and respiration (right to left):

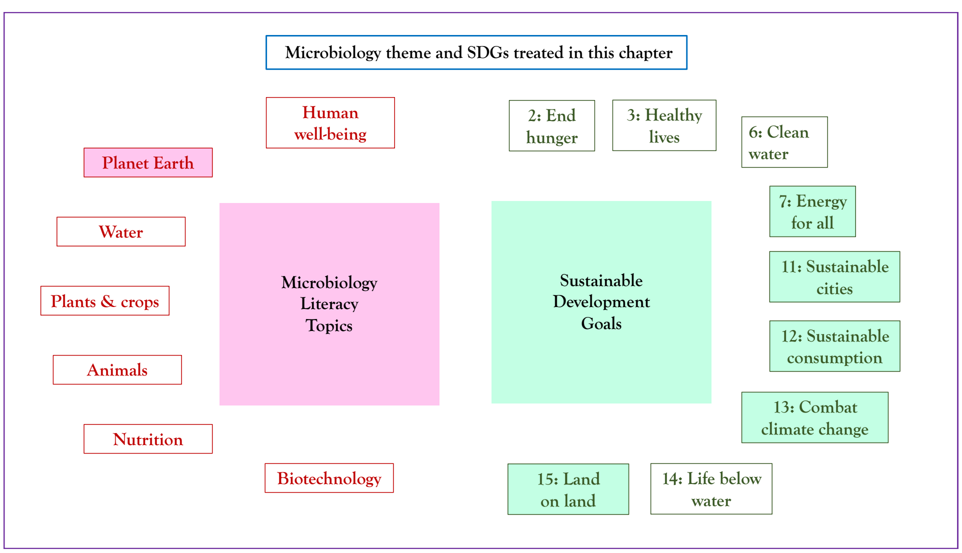
$$CO_2 + H_20 \leftrightarrow C_6H_{12}O_6 + O_2$$

carbon dioxide + water ↔ glucose + oxygen gas

are balanced on a planetary scale along with other processes that affect atmospheric gas composition over millions of years.

The conditions that make Earth habitable to humans today are maintained by a network of chemical reactions (biogeochemical cycles). These reactions, including respiration and photosynthesis, are driven by life using a small set of proteins, which are nanoscale biological machines. Many of the same proteins are found in all lifeforms visible to our naked eyes. However, they evolved early in Earth's history in microbes. Microbes are the library of life: they record the evolution of all of us. We, humans, are a hybrid of microbes. But long, long ago, there were no plants or animals, only microbes; they made Earth habitable.

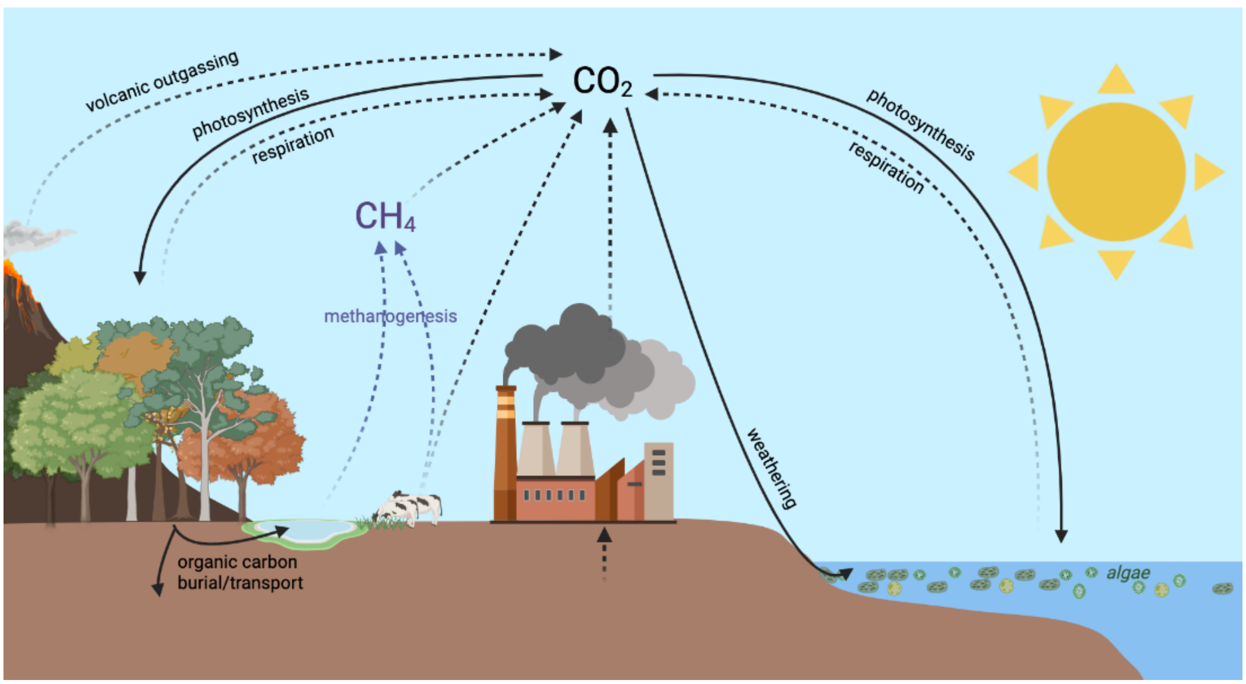
The Microbiology and Societal Context



Microbiology: microbial metabolism and metabolic diversity; evolution of proteins. *Context:* life-geosphere co-evolution; biogeochemical cycling; Earth systems thinking. *Sustainability issues:* understanding connections between nutrient/carbon pollution, changes to ecosystem health and function locally and globally; use of microbial metabolism and proteins in sustainable practices and renewable energies

Protein nanomachines: The Microbiology

1. Earth's current habitability to humans is maintained by a network of chemical reactions driven by life. The Earth is an integrated system composed of a biosphere, geosphere, hydrosphere and atmosphere. These "spheres" interact through the flow of matter and energy. The major building blocks of the biosphere (life) are hydrogen, carbon, nitrogen, oxygen, sulfur and phosphorus. These "big six" elements are continuously recycled through Earth's four spheres, taking on different chemical forms. Both biological and geologic/physical processes mediate the chemical reactions which drive Earth's biogeochemical cycles, determining the distribution and chemical form of the primary elements of life. The distribution and form of these elements affects Earth's habitability.



Simplified carbon cycle. Carbon dioxide (CO_2) is converted to organic carbon forms by plants and algae via photosynthesis and to other inorganic forms via chemical weathering (solid lines). CO_2 is produced during respiration (by plants, animals, and microbes), and when humans burn ancient organic matter i.e., fossil fuels (dashed lines). Some anaerobic microbes (which can be found inside cow stomachs, among other places) produce methane (CH_4) instead of CO_2 (purple lines). However, CH_4 is not very stable and turns into CO_2 in the atmosphere relatively quickly after it is produced (within decades). The processes shown here represent only a subset of the ways that carbon is cycled through the Earth system.

Let's explore these concepts by thinking about the carbon cycle. Carbon in the atmosphere exists primarily in two forms – carbon dioxide (CO_2) and methane (CH_4). Both chemical forms are greenhouse gases, meaning that they insulate the Earth by reducing the escape of Earth's heat to space. When greenhouse gas concentrations rise, the Earth warms. Methane is a much stronger greenhouse gas; however, it is relatively unstable and deteriorates to carbon dioxide after about a decade. Thus, both the amount of carbon in the atmosphere and its chemical form play an important role in setting a comfortable temperature for life.

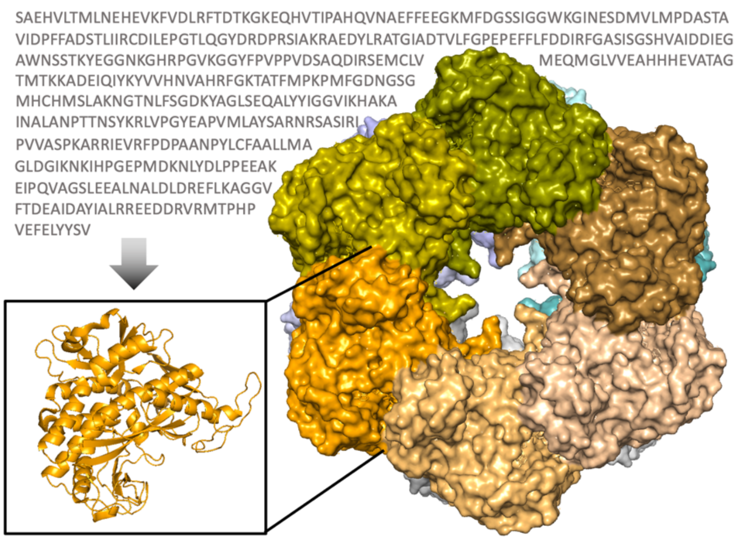
Methane is continuously added to the atmosphere when certain anaerobic microbes respire (methanogenesis). Carbon dioxide is continuously added to the atmosphere by aerobic respiration, volcanic outgassing and other processes. While methane decays to carbon dioxide after a decade or so, carbon dioxide is very stable and can remain in the atmosphere for much longer – many millions of years. Carbon dioxide in the atmosphere can be transferred to the biosphere, geosphere and hydrosphere through several processes. Plants and algae convert the carbon in carbon dioxide to organic forms via photosynthesis; unlike carbon dioxide, organic carbon contains hydrogen that is bound directly to a carbon atom. Organic carbon can then be stored in the biosphere as living biomass (e.g., trees and grasses), or in the geosphere as soils and sediments. Non-biological processes are also very important. From example, carbon dioxide in the atmosphere is transferred to the hydrosphere (e.g., the oceans) due to mixing and equilibration.

2. An organism's metabolism determines its biogeochemical impact. Life needs materials to grow (our big six major elements plus a few others) and energy to fuel that growth. These ingredients come from our environment, and it is to our environment that we return our waste. For example, methane and carbon dioxide are both waste products of different types of respiration, as discussed above. As humans, we assimilate nutrients from our food, but we also "burn" (respire) some of this organic material as fuel. We use the oxygen we breathe in this process. The result is the release of energy stored in organic chemical bonds and carbon dioxide as a waste product. By driving the flow of matter and energy, metabolic reactions shape both life and its environment.

Metabolism (life-sustaining chemical reactions within an organism) can be defined by an organism's energy and carbon sources.

Metabolism	Energy source	Carbon source	Example organisms
Autotrophs			
*Photo*autotroph	Light	CO_2	Plants, algae
*Chemo*autotroph	Chemical compounds (inorganic)	CO_2	Some prokaryotes
Heterotrophs			
*Photo*heterotroph	Light	Organic compounds	Some prokaryotes
*Chemo*heterotroph	Chemical compounds (organic)	Organic compounds	Animals, fungi, many prokaryotes

3. Life shapes its environment using certain proteins, which function as tiny machines. Metabolic reactions are carried out by life using a small set[1] of proteins. Proteins are one of the most important macromolecules in biology (along with nucleic acids, lipids and carbohydrates). Fundamentally, proteins are chains of amino acids that twist and curl into complex structures. As each amino acid exhibits distinct chemical properties, their sequence determines how the chain will fold. Bonds between certain amino acids will cause the chain to twist into helices or form sheet-like structures. Many proteins are highly complex structures made up of multiple chains. Often, one protein will be composed of several identical chains, creating beautifully symmetric molecular structures.

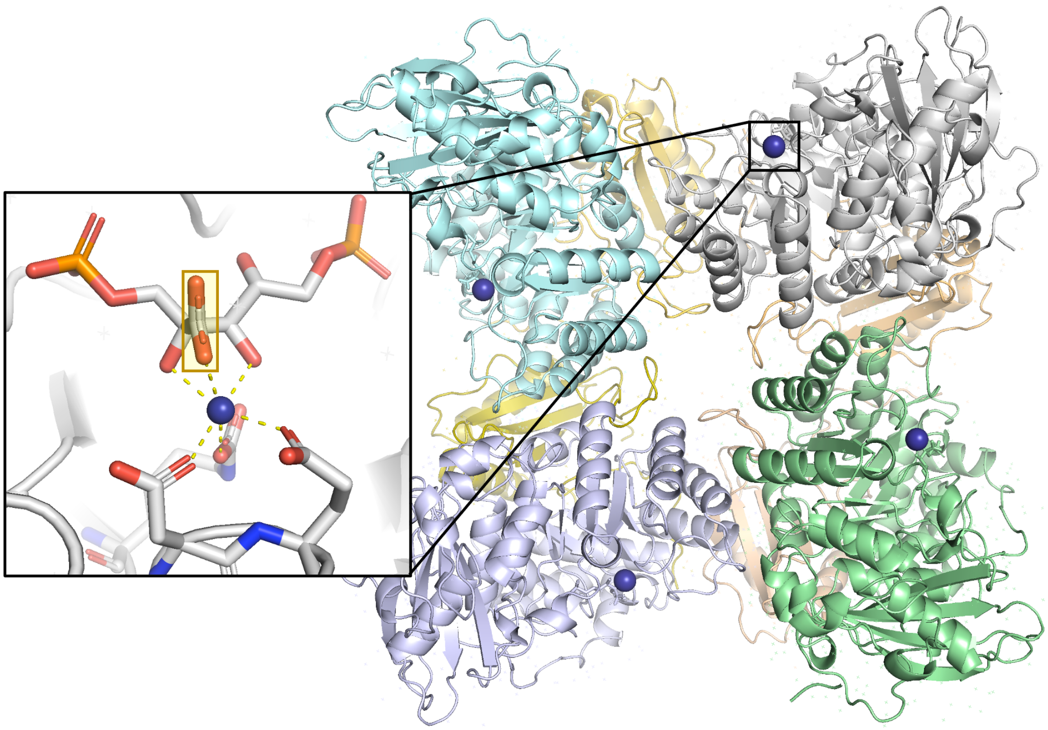


Amino acid sequence dictates protein structure. Amino acids (each represented by a letter in gray) form chains, which fold and curl into small proteins (ribbon structure shown in gold). These protein molecules can assemble, each acting as a subunit of a more complex protein (multicolored surface structure). The protein complex shown here is glutamine synthetase—a key enzyme in nitrogen metabolism. More information on the structure and function of glutamine synthetase can be found in this article from the Protein Data Bank: https://pdb101.rcsb.org/motm/30. The structure depicted can be found in the Protein Data Bank as entry 1FPY.

A protein's structure determines its function. Some proteins are used as building materials while others, like the ones that drive metabolism, function as nanoscale machines. Collagen, for example, is a protein used to build your bones and connective tissues; it is rich in an amino acid called proline, which causes its chains to wind together into long fibrils (nanometer-scale fibers). These fibrils are excellent building materials because they are both strong and flexible. Other proteins, called enzymes, do work: They catalyze chemical reactions that would not otherwise occur. Enzymes have active sites to which only specific compounds (substrates) can bind due to their shape and chemical properties (like a key fitting into a lock). When a substrate is bound, the enzyme's shape shifts. This 'conformational shift' positions the substrate so that it is near other reactants in a specific orientation. In this new position, the activation energy of the reaction is lowered and the reaction can proceed. Let's look at an example from the carbon cycle.

[1]Here, we refer largely to one class of enzyme known as oxidoreductases. Oxidoreductases transfer electrons from one molecule to another. Electron transfer drives the reactions that sustain life (metabolism). However, many other enzymes which do not transfer electrons play very important roles in supporting the flow of energy and matter within a cell, and between a cell and its environment.

Using energy from the sun, plants and algae convert gaseous CO_2 to organic carbon. This reaction is catalyzed by the protein Rubisco[2] in a multistep process. First, Rubisco binds CO_2 and a small sugar molecule—a chain of five carbon atoms called ribulose bisphosphate—in close proximity; this causes ribulose bisphosphate to undergo a minor change in its chemical structure. The two molecules now bond readily, forming a molecule composed now of six carbon atoms. Second, this lengthened chain breaks in half, creating two chains with three carbon atoms each. Some of these three-carbon molecules are ultimately recycled while others are subsequently converted into simple sugars.



A protein's three-dimensional structure determines its function. Rubisco (depicted on the right as a ribbon with subunits represented by different colors) uses magnesium ions (dark purple) to coordinate both CO_2 and ribulose bisphosphate. This is shown in the inset panel: Ribulose bisphosphate is bound above the magnesium ion with the CO_2 molecule (highlighted by yellow box) already attached. Red, blue, and orange indicate oxygen, nitrogen, and phosphorus atoms. Bonds are shown as dashed yellow lines. More information on the structure and function of Rubsico can be found in this article from the Protein Data Bank: https://pdb101.rcsb.org/motm/11. The structure depicted can be found in the Protein Data Bank as entry 8RUC.

4. Microbes maintain a record of protein nanomachines through time. Most multicellular organisms rely on the metabolic strategies that are most efficient on Earth today. These include chemoheterotrophs like us who breathe oxygen and plants which produce oxygen via photosynthesis. The nanomachines which drive these reactions evolved first in microbes and are

[2]RuBisCO is common shorthand for the protein's full name, Ribulose-1,5-bisphosphate carboxylase-oxygenase. It is one of the most abundant proteins on the planet and can comprise up to half of the soluble proteins in the leaves of some plants. While most autotrophic organisms rely on Rubisco to capture CO_2, a small number use alternative enzymes.

still found in the genomes of many microorganisms. But these more efficient metabolic strategies are only a few of many options found in nature. For example, some chemoheterotrophic microbes use different nanomachines to respire using different inorganic compounds in place of oxygen (e.g., nitrate, sulfate). Other microbes photosynthesize using a putative predecessor of one of the light-harvesting nanomachines found in modern plants. Some of these organisms (e.g., green sulfur bacteria) use hydrogen sulfide in place of water. Today, these types of metabolic strategies are usually relegated to anoxic sediments, hot springs and other peculiar environments. Nevertheless, they play very important roles in Earth's biogeochemical cycles. Moreover, they represent a record of evolution's past innovations. We can therefore think of microbes as the 'libraries of life': they store the instructions for making the most important nanomachines on Earth, including many of those on which you and I rely.

5. The evolution of protein nanomachines fundamentally changed Earth. Evolution describes an accumulation of changes that result in new functions. Small differences in the blueprints of proteins, genes, occur randomly during reproduction. We can think of this as being akin to errors made when transcribing text: If you were to try to copy a whole novel by hand, you might make some mistakes. Maybe you would write "here" instead of "there", or maybe you would lose your place and repeat a section which you'd already copied. These sorts of errors may make the text unintelligible, or may not matter at all. But some of these errors could change the meaning of the text in a manner that is lyrical and innovative. When random changes in an organism's genetic code result in a function that is useful within the context of that organism's environment, then that organism will be more likely to survive and create offspring which bear the new function.

The nanomachines which enable life to make a living, and which drive Earth's biogeochemical cycles, each evolved because they increased the probability of a microbe's survival under the environmental conditions of the time. As different nanomachines evolved, they fundamentally shaped the Earth by redistributing key elements or changing which chemical forms were most abundant. These changes in environmental conditions then led to new evolutionary innovations. Let's look at a few examples.

Example 1: Nitrogen is a key ingredient for life. Without nitrogen, cells cannot replicate their genetic code or make proteins. Virtually all of the nitrogen on Earth occurs in a gaseous form (dinitrogen gas) that is relatively unreactive. This means that it takes a lot of energy to change its form, and is not easily used by life. Many, many years ago (>3.5 billion years ago), when Earth was young, life had no tools for transforming gaseous nitrogen into a usable form like ammonium. Instead, the first microbes had to rely on very inefficient non-biological processes like lightning to transform gaseous nitrogen into a usable form. As microbes became more numerous, usable forms of nitrogen became a limiting factor for growth of nascent microbial communities. Ultimately, a new nanomachine evolved that was able to convert gaseous nitrogen into ammonia[3]. This nanomachine, called nitrogenase, enabled the first microbial communities to flourish and become a dominant force on the planet.

[3]Ammonia (NH_3) and ammonium (NH_4^+) differ by a proton, which is the nucleus of a hydrogen atom. The two forms are readily interconverted. The presence of the proton is a function of the pH of the environment. At ocean pH of about 8.1 about 93% is in the form of ammonium. Inside a cell, at pH 7.2, about 99% is in the form of ammonium.

Example 2: Some of the earliest microbes made a living through photosynthesis but, unlike modern plants, the nanomachinery used by these organisms to harness energy from the sun did not produce ***oxygen***. Like in the case of nitrogen fixation (above), as photoautotrophs began to flourish, a new nanomachine evolved and rose to ecological prominence. In the process of transducing light energy to chemical energy, this new nanomachine (Photosystem II) splits water. A by-product of this reaction is oxygen. The evolution of this nanomachine caused oxygen gas to become a major component of Earth's atmosphere starting ~2.4 billion years ago; about half-way through the planet's history.

Without oxygen gas in the atmosphere, complex and biodiverse ecosystems as we know them would not exist. This is because aerobic respiration supplies 18 times more energy for growth than anaerobic respiration. In other words, when a cell uses oxygen to break down organic matter (respire) instead of an alternative oxidant, more energy is produced and the cell can carry out more chemical reactions. Oxygen allowed respiration to be "supercharged". In sum, the invention of Photosystem II enabled the evolution of complex heterotrophic, multicellular organisms. Indeed, there were no animals before oxygen became a significant component of Earth's atmosphere.

6. Today, humans are altering Earth's atmosphere. Human activities are disrupting the cycling of elements on Earth. One of the major ways in which we are altering biogeochemical cycles is by combusting fossil fuels. By removing carbon from long-term storage in the geosphere and pumping it into the atmosphere as carbon dioxide, we are – in effect – increasing the rate of planetary "respiration".

These types of human-driven biogeochemical changes alter the availability of certain habitats to which different organisms have grown accustomed. But there is more to the story than that. Changing the environment affects which organisms thrive. This, in turn, affects Earth's biogeochemical cycles.

One example of this is the loss of oxygen in many coastal waterways due to eutrophication. In the early 20th century, humans figured out how to do what evolution had only mastered once before – convert gaseous nitrogen to a usable form (ammonia)[4]. Much like microbes early in Earth's evolution, humans were potentially going to starve unless we could make ammonia for the plants that feed and serve us. In other words, we needed to produce more ammonia in order to continue to expand our population. Early in the 20th century, we figured out how to do that, however, much of the nitrogen that we have been putting on croplands in the past century has washed off into rivers and coastal waters. Certain algae are very adept at using this nitrogen and, in many places, their growth is also limited by nitrogen. Consequently, they grow rapidly when easily usable nitrogen forms are added to their water. Once the new nitrogen is all gone, the algae die. The organic matter which they produced is then consumed by heterotrophic microbes who respire oxygen. This pattern leads to the depletion of oxygen in coastal waterways, killing fish and other multicellular organisms. These oxygen deficient zones, once developed, are home to many anaerobic microbes similar to those that existed on the ancient Earth.

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[4]The industrial conversion of gaseous hydrogen and nitrogen to ammonia is called the Haber-Bosch process after the inventor (Fritz Haber) and the engineer who made it commercially viable (Carl Bosch). Both won Noble Prizes.

Relevance for Sustainable Development Goals and Grand Challenges

Microbial nanomachines and Earth's biogeochemical cycles relates to several sustainable development goals (*specific aspects in italics*), including

- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all** (*development of sustainable energy strategies, renewable energy sources).* Developing and choosing the best energy sources requires an understanding of how those energy sources will affect the Earth system as a whole. Good sources of energy are those that do not fundamentally shift the biogeochemical balance of the planet. This can mean either not altering the cycling of elements, or ensuring that our disruptions are balanced. If we continue to combust fossil fuels and thus emit carbon dioxide, for example, then we need to ensure that we are also removing carbon dioxide from the atmosphere. One option is to transfer carbon dioxide from the atmosphere to the geosphere (e.g., store it in rocks or building materials like concrete) or biosphere (e.g., increase the growth of woody plants). Another option is to combust organic matter that was recently produced from carbon dioxide (e.g., algal biomass) instead of ancient organic matter that has been buried (fossil fuels). However, we have been pumping carbon dioxide into the atmosphere for over a century and, consequently, need to starting removing more than we add to make a significant difference in coming decades.

  Some nanomachines may be particularly important in developing renewable energy sources. For example, chemists and engineers today are studying nanomachines found in microbes which produce hydrogen gas (hydrogenases and nitrogenase). Many people hope to use these nanomachines, or to engineer better versions of them, to produce hydrogen as fuel. Burning hydrogen does not led to a production of carbon dioxide, only water.
- **Goal 11. Make cities and human settlements inclusive, safe, resistant and sustainable** (*sustainable urban planning, waste management).* We can think about maintaining a balanced flow of energy and matter on local as well as global scales. What materials do we import? What do we export? What strategies can we design to improve recycling locally? For example, cities bring in a lot of food to feed everyone and then need to deal with the human waste. This waste includes a lot of nutrients like nitrogen and organic matter. Dumping this material into waterways can cause eutrophication (and spread disease). To combat this issue, many cities use aerobic and anaerobic microbes to remove nutrients and organics. However, these processes do not, of course, make carbon and nitrogen disappear. They convert these elements to gaseous forms, which can affect human health and contribute to climate change[5]. Increasingly, however, people are exploring how to safely recycle human waste to nourish crops and provide energy. Many of these strategies leverage the microbes with diverse metabolisms to control the end-products of processing.
- **Goal 12. Ensure sustainable consumption and production patterns** (*achieve sustainable production consumption practices, pollution remediation).* Developing sustainable consumption and production patterns on both small and large scales challenges us to think of our environment as a system of which we are only one aspect. As discussed for Goal 11, all compounds that are produced must be consumed and vice versa in a balanced system. Microbes

[5] In addition to carbon dioxide and methane production, incomplete processing of nitrogen in the form of nitrate produces the greenhouse gas, nitrous oxide (laughing gas).

can help us. For example, some microbes build nanomachines that break down certain types of plastic. Today, scientists are studying these organisms and their nanomachines with the goal of designing new tools for coping with plastic waste and developing sustainable plastic management practices. Other microbial nanomachines (lignolytic enzymes) can be used to break down industrial food waste products. These nanomachines may be helpful in developing strategies to use these waste products as a fuel source and for making new, biodegradable materials to replace conventional plastics (which are made from petroleum).

- **Goal 13. Take urgent action to combat climate change and its impacts** *(reduce greenhouse gas emissions).* Certain anaerobic microbes represent a major source of two important greenhouse gases, methane and nitrous oxide, which exacerbate global warming. The microbes that produce these gases are almost always found in environments with no oxygen, including in the guts of certain animals like cows. Human activities (e.g., eutrophication, cattle farming) are expanding the niche for these organisms.
- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss** *(pollution remediation).* Some microbes release nanomachines into the environment (extracellular enzymes) which degrade harmful chemical compounds. These include compounds that do not easily degrade like plastics (discussed under Goal 12), as well as ones those that are toxic and cause biodiversity loss (e.g., polycyclic aromatic hydrocarbons, polychlorinated biphenyls). Microbes in the environment are already helping to remediate human pollution, but their work is slow. Researchers today are exploring how these microbes, their nanomachines, or synthetic versions of their nanomachines could be deployed to clean up contaminated sites more efficiently.

Potential Implications for Decisions

1. ***Individual***
   - **a.** How do I view myself as part of the integrated Earth system?
     - i. What do I consume?
     - ii. What do I produce?
     - iii. Where does my food come from?
     - iv. Where does my oxygen come from?
     - v. What happens to my waste?
   - **b.** The atmosphere is the conduit that connects all of Earth's ecosystems. How do the gases which I produce affect ecosystems and populations around the world? What choices can I make in my own life to reduce greenhouse gas emissions from my activities?

2. ***Community policies***
   - **a.** What materials are brought into my community? What materials do we export? How can we improve recycling locally?
   - **b.** How do we manage our waste? (How do we use microbes in this process?) Can we do it better?

   c. Is there a lot of carbon sequestered in or around my community (e.g., in forests, seagrass beds)? How can we ensure that it stays in storage? Are there choices that we can make to improve local carbon storage?

3. ***National policies***
   - **a.** Greenhouse gas production and carbon management
   - **b.** Preventing eutrophication
   - **c.** Implementing environmental remediation efforts

Pupil Participation

1. ***Class discussion***:
   - **a.** How does our local community impact global ecosystems and populations?
   - **b.** How do you interact chemically with your environment? What do you consume and where does it come from? What waste do you produce and where does it go?

2. ***Pupil stakeholder awareness***
   - **a.** What lifestyle choices do you, your family, and your neighbors make that contributes to the production of greenhouse gases?
   - **b.** What is your community already doing to positively impact sustainable living?
   - **c.** How can you and your classmates address climate change at your school?

3. ***Exercises***
   - **a.** Billions of tons of food waste end up in landfills globally each year. Collect data from local restaurants about how much food they get rid of in a week or month and what they do with it. What do you think the impact of food waste is? What ideas do you have to address it?
   - **b.** Get to know your local landfill. Design an investigation to understand in what ways your local landfill contributes or combats climate change.
   - **c.** Create a survey and collect data from friends, family and neighbors to understand their consumer and producer patterns in your community. How do these patterns affect surrounding communities and ecosystems? How do they affect the Earth on a global scale?
   - **d.** Create a model of the perfect community of the future, designed for sustainability. Consider how and where food is produced and waste is managed. What role do microbes (and their nanomachines) play in this future community?

The Evidence Base, Further Reading and Teaching Aids

On the evolution of life and Earth's biogeochemical history

Falkowski, Paul G. *Life's Engines: How Microbes Made Earth Habitable*. Princeton University Press, 2015.

Falkowski, Paul G., Tom Fenchel, and Edward Delong. 2008. "The microbial engines that drive Earth's biogeochemical cycles." *Science* 320(5879): 1034-1039. https://doi.org/10.1126/science.1153213

Canfield, Donald E. *Oxygen: A Four Billion Year History*. Vol. 20. Princeton University Press, 2014.

Langmuir, Charles H., and Wally Broecker. *How to Build a Habitable Planet*. Princeton University Press, 2012.

Hazen, Robert M. *The Story of Earth: The first 4.5 Billion Years, from Stardust to Living Planet*. Penguin, 2013.

On microbes and sewage treatment

Kumar, Vinod, A.K. Chopra, and Ajendra Kumar. 2017. "A review on sewage sludge (Biosolids) a resource for sustainable agriculture." *Archives of Agriculture and Environmental Science* 2.4: 340-347. https://doi.org/10.26832/24566632.2017.020417

On microbes/nanomachines that degrade plastic

Ball, Phillip. 2017. Plastics on the menu. *Nature Materials* 16: 606. https://doi.org/10.1038/nmat4912

Jiménez, Diego Javier, et al. "Merging plastics, microbes, and enzymes: highlights from an international workshop." *Applied and Environmental Microbiology* 88.14 (2022): e00721-22. https://journals.asm.org/doi/pdf/10.1128/aem.00721-22

https://www.youtube.com/watch?v=nWfBvRm4640 In this video, a scientist demonstrates an enzyme degrading plastics in less than one day.

https://pdb101.rcsb.org/motm/277 A "Molecule of the Month" spotlight on plastic-eating enzymes from the Protein Data Bank.

Ongoing research on life's origin, evolution, and the search for life on other planets

https://www.youtube.com/watch?v=DGTPPy2fNyc This video discusses ongoing research led by Dr. Paul Falkowski (Rutgers University) on the origin and evolution of key nanomachines.

https://astrobiology.nasa.gov/ Here, NASA highlights ongoing research and new discoveries.

http://prebioticchem.info/seminar-series/index.html This link contains a list of publicly available scientific seminars on prebiotic chemistry and early Earth environments.

https://astrobiology.nasa.gov/ask-an-astrobiologist/episodes/ The NASA *Ask an Astrobiologist* show explores research on the search for life in the universe.

Resources for teaching evolution

https://www.evolutionsociety.org/content/education/resources-for-teachers-and-students.html Resources for teaching evolution from the Society for the Study of Evolution including programs, courses and workshops for teachers

Resources for exploring protein structure and function

https://pdb101.rcsb.org/ The Protein Data Bank (PDB) is the world's largest repository of protein structures. Here, the PDB offers resources for learning about proteins.

https://pdb101.rcsb.org/learn/videos Here, the PDB shares videos illustrating how proteins function, including one on "How enzymes work".

Resources for teaching biogeochemical cycles and climate change

https://www.us-ocb.org/science-support/outreach-education/ Resources from the Ocean Carbon and Biogeochemistry group including video lessons on the carbon cycle and infographics developed for educational use by scientists

https://www.nsta.org/science-teacher/science-teacher-august-2019/carbon-cycle-and-climate-change Lesson plans on the carbon cycle from the National Science Teaching Association

https://www.youtube.com/watch?v=klAE-L8xTp0 This video shows the seasonal expansion and contraction of photosynthesis (green), referred to as Earth "breathing".

Related children's books

Find the Sunlight Series (books about our living planet by writer-illustrator Molly Bang and ecologist Penny Chisholm) and resources for use in the classroom here: https://thesunlightseries.com/

Glossary

aerobic: Requiring oxygen (O_2)

activation energy: The minimum amount of energy necessary to start a reaction

active site: The site on an enzyme where a substrate binds and undergoes a chemical reaction

amino acids: The building blocks of proteins; simple organic molecules which contain an amino group ($-NH_2$) on one end and a carboxyl group ($-COOH$) on the other. Each amino acid has a unique chemical group (side chain) which affects its chemical properties.

ammonium/ammonia: A reduced, inorganic form of nitrogen with the chemical formula NH_4^+ (ammonium) or NH_3 (ammonia). Ammonium and ammonia are readily interconverted and differ only by one proton, which is a function of the pH of the environment.

anaerobic: Requiring an absence of oxygen (O_2)

atmosphere: The mass of gases which envelop a planet; the gravity of the planet keeps these gases from being lost to space

biogeochemical cycles: The cycling of chemical elements through Earth's biosphere, geosphere, atmosphere, and hydrosphere

biosphere: The biological component of a planet; the sum of all ecosystems and organisms

catalyze: To cause or accelerate a chemical reaction using an agent that is not consumed in the process (a *catalyst*)

climate: The average state of the atmosphere on long timescales (>30 years)

enzyme: A protein which causes a particular chemical reaction to occur

electron: A stable, negatively-charged subatomic particle that orbits atomic nuclei (protons and neutrons)

eutrophication: The enrichment of nutrients (commonly nitrogen and phosphorus) in a body of water above healthy limits for the local ecosystem. Under eutrophic conditions, fast-growing algae can overwhelm the ecosystem, potentially leading to the development of oxygen deficient zones. Deoxygenation occurs because algal organic matter is consumed by heterotrophic bacteria.
inorganic: Referring to compounds that do not contain carbon-hydrogen and/or carbon-carbon bonds and are not derived from life
photosynthesis: The process by which life harvests energy directly from the sun to produce organic matter
protein: Biomolecules composed of folded amino acid chains
proton: A stable, positively-charged subatomic particle which, along with neutrons, makes up the nucleus of an atom; the number of protons in the nucleus of an atom determines its chemical properties
gene: The basic unit of heredity passed from parent to child; a sequence of distinct molecules (nucleotides) which encodes instructions for making proteins
genome: The complete set of genes in an organism
geosphere: The solid, inorganic component of a planet; the sum of all rocks and minerals
greenhouse gas: An atmospheric gas which contributes to planetary warming by preventing energy radiating from Earth (longwave radiation) to escape
habitability: The potential for an environment to bear life
hydrosphere: The water on a planet's surface including its oceans, seas, lakes, and rivers
metabolism: The set of life-sustaining chemical processes which are carried out within organism; includes the processes by which an organism acquires energy and grows
methanogenesis: Anaerobic respiration which produces methane
organic: Referring to compounds that contain carbon-hydrogen and/or carbon-carbon bonds and are produced or derived from life
oxidant: A substance which can accept electrons during oxidation-reduction reactions
oxygen deficient zones: A region within a body of water that is devoid of oxygen, typically because oxygen removal via respiration exceeds oxygen resupply via mixing
protein: A biological molecule comprised of one or more chains of amino acids, which fold into a particular structure
reactant: A substance that undergoes a chemical reaction
respiration: The production of energy via the oxidation of (removal of electrons from) complex organic substances. In aerobic respiration, oxygen is used as an oxidant (electron acceptor). In anaerobic oxidation, other chemical substances (e.g., nitrate and sulfate) are used.
substrate: A molecule binds to and is acted on by an enzyme

Additional Notes

Cover art by D. Blankmann depicts the balance between photosynthesis (by the tree) and aerobic respiration (by both the children and the tree). The proteins shown represent key parts of the metabolic pathways which mediate these processes. For photosynthesis, photosystem I (light-harvesting protein) and Rubisco are shown, representing the light (energy production) and light-independent (organic carbon production) reactions. (Note: Only photosystem II actually produces O_2.) For respiration, a hexokinase and pyruvate dehydrogenase are depicted; these proteins play important roles in the breakage and oxidation of organic carbon, which ultimately releases energy, CO_2 and H_2O. Please note that these metabolic pathways are complex and involve dozens of different proteins in addition to those shown. The PDB identification codes for the four enzymes shown are: 1JB0, 1GK8, 1BDG and 3EXG.

Determining the structure of proteins in the laboratory is an arduous process. The protein structures shown here were resolved by:

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