Microbial cycling of greenhouse gases

Mother: I saw on the internet someone lighting a piece of ice on fire! How is that possible?

Credit: J. Pinkston and L. Stern (USGS), USGS. Public domain
Ice on fire! Frozen methane ice can be burned.

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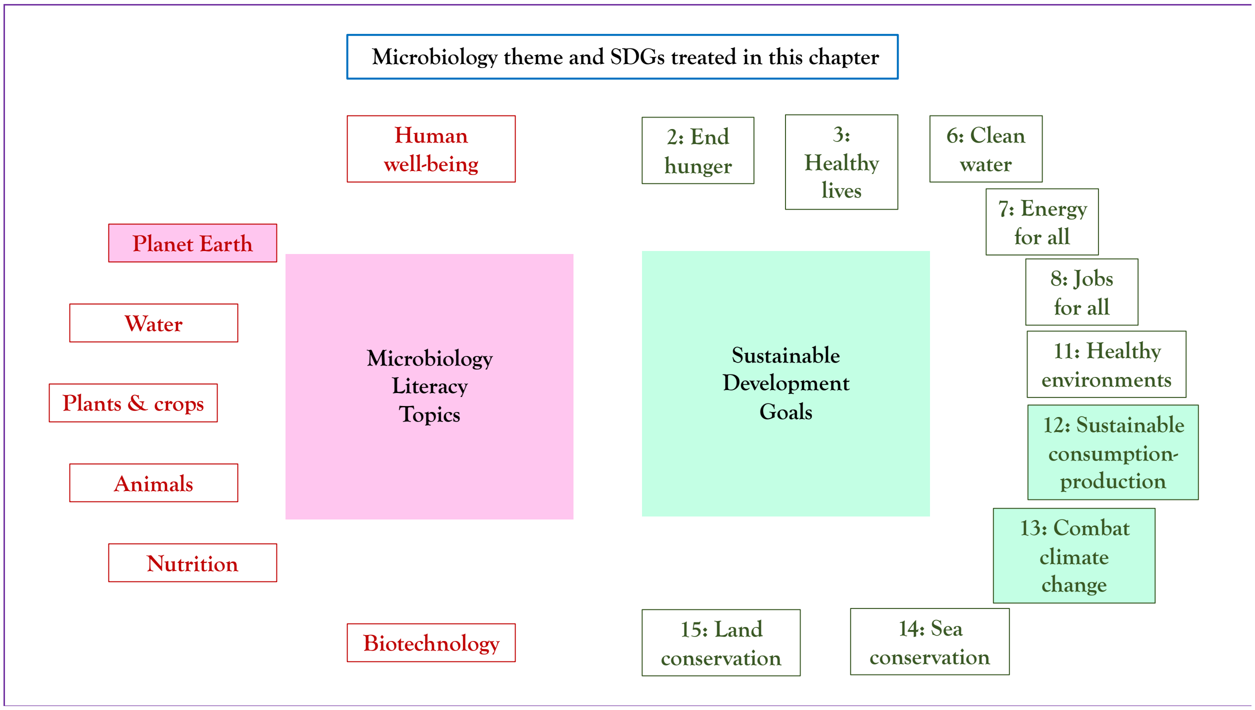
Storyline

Climate change is an ongoing problem that the world is facing, mostly due to humans burning massive amounts of buried carbon in the form of **fossil fuels** and emitting the gaseous wastes into the atmosphere. When we burn fossil fuels, carbon dioxide is the main **greenhouse gas** that's produced. But there are other human activities that result in emissions of non-carbon dioxide greenhouse gases, mainly **methane** and **nitrous oxide**. Methane and nitrous oxide are greenhouse gases that hold about 30 and 300 times more heat, respectively, than carbon dioxide on a molecule-to-molecule basis, and so are much more powerful greenhouse gases than carbon dioxide. A portion of human-generated methane and nitrous oxide is from mining and combustion of fossil fuels, but the majority is from changing the landscape (e.g. deforestation) and growing food (both animals and crops). Microorganisms are the gatekeepers of methane and nitrous oxide emissions that are not from fossil fuel sources. Human activities have altered environments in such a way that promotes growth and metabolism of the greenhouse gas producers over processes that consume these same gases. The result is that more methane and nitrous oxide is now produced and emitted to the atmosphere than the amount either consumed by microorganisms or by chemical reactions that usually keep these gases in balance. Thus, the production-consumption cycle of methane and nitrous oxide has been disrupted as a consequence of altering natural ecosystems in order to generate more human resources, like food and fuel. Resetting the balance of the greenhouse gas production-consumption cycle requires an understanding of how microorganisms perform this cycle of climate-active gases, how human alterations of landscapes and ecosystems influence these cycles, and how we can alter our societal behaviors and practices to regain cycle equilibrium and prevent further accumulation in our atmosphere.



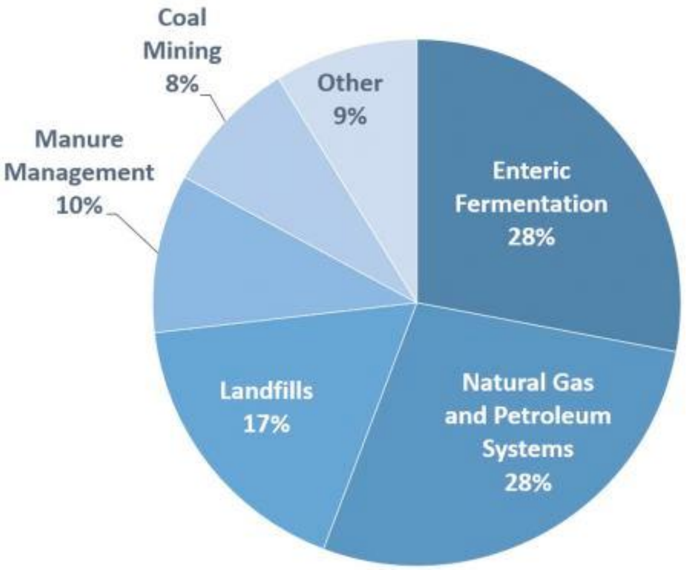
The Microbiology and Societal Context

The microbiology: methanogens, methanotrophs, nitrifiers, denitrifiers, agriculture, anoxic. *Sustainability*: healthy environments, greenhouse gases, food production, climate change

Greenhouse gases: The Microbiology

1. ***What does methane have to do with microorganisms?*** Methane (CH_4) is a greenhouse gas that is estimated to be about 30 times more potent than carbon dioxide (CO_2) in holding in heat. Currently, methane accounts for about 28% of the greenhouse effect. Methane is actively cycled by microorganisms, as some have the ability to produce methane, while others can consume it. Under balanced conditions, microbial production of methane is nearly equivalent to microbial consumption, so little accumulates in the atmosphere. Early in the Earth's history (about 3.5 billion years ago) methane was 1,000 times more concentrated in the atmosphere than it is today. But as the biosphere evolved, methane concentrations decreased in the atmosphere to sustain about 1.7 parts per million and the microbial methane cycle kept the balance between biosphere and atmosphere in check. Only very recently has human activity begun to disrupt the methane balance, resulting in accumulation of methane in the atmosphere where it acts as a potent greenhouse gas.

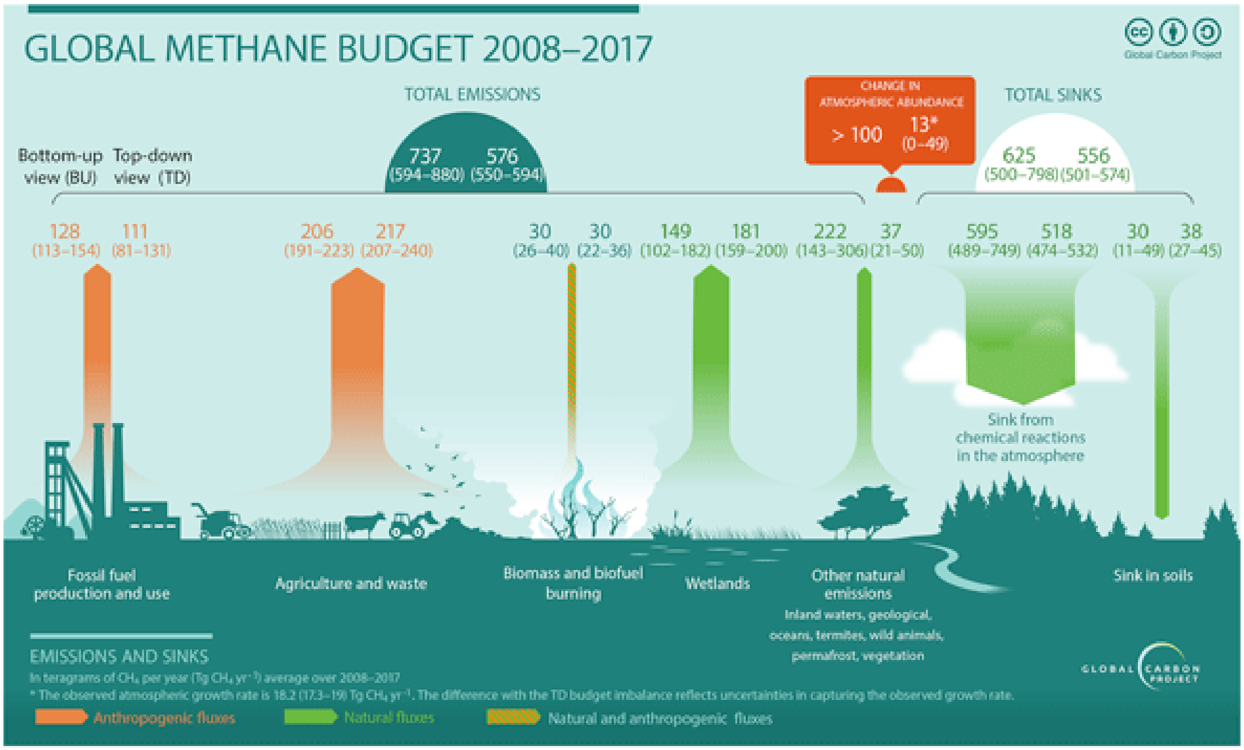
Methane is generated by geological (thermochemical) and biological processes. Large reserves of methane are stored in an ice-like form in permafrost and marine sediments that can be unearthed and burned (see cover photo). Human activity exacerbates the production of methane in two ways: by fossil fuel combustion and coal mining (accounting for ~36% of human-caused methane), and by accumulating and concentrating organic materials into areas where oxygen is at a low concentration and the methane-generating microorganisms are abundant (~64% of human caused methane). Areas that match the latter description, where microbial methane production is high, include landfills (where most of our garbage is dumped), rice paddies and marshes, which are flooded most times of the year, and animal husbandry operations – from manure accumulation and within the animals themselves (e.g. cows).



Major Methane Sources: US-EPA, 2018. Enteric fermentation = inside of ruminant animals.

The microorganisms that generate methane are called **methanogens**, combining "methano" for methane, and "gen" for generate. Methanogens are not bacteria; rather, they are classified as **archaea**. The methanogenic archaea have many interesting and unique features that enable them produce methane. One of these features is that they thrive in environments that are completely devoid of oxygen, or what we refer to as **anoxic** ecosystems. Unlike now, early Earth was entirely anoxic, and methanogens are considered one of the most ancient types of microbes that evolved on Earth. This means that the biological production of methane is also ancient to our planet and could represent a common metabolism on extraterrestrial planetary bodies that have similar chemical compositions.

On the flip side, methane consumption is performed by microorganisms called **methanotrophs**, or literally "methane (methano) –eaters (trophs)." Methanotrophs are more diverse than methanogens: there are both bacterial and archaeal methanotrophs, they can consume methane in the presence or absence of oxygen, and they have evolved multiple times over the course of Earth's history. Methanotrophs are the only known biological sink for methane and consume about 10% of the total methane emitted from the biosphere. The remaining 90% of methane is eventually destroyed through chemical reactions in the atmosphere, but not quickly enough to stop it from acting for a time as a potent greenhouse gas and contribute to global warming.



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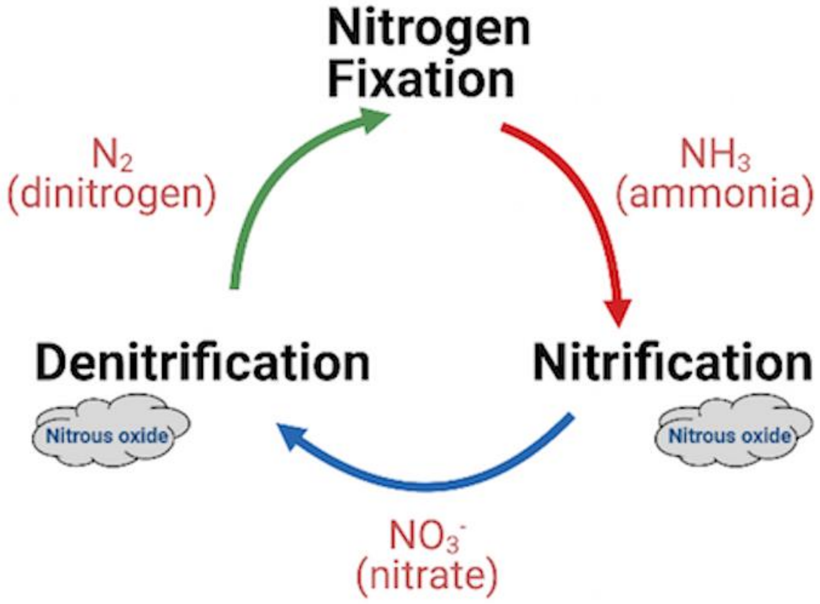
2. ***What do microorganisms have to do with laughing gas, a.k.a. nitrous oxide?*** Nitrous oxide is commonly known as a popular anesthetic in dentistry practices that was originally discovered by Joseph Priestley in 1772. The gas causes euphoria and earned the name "laughing gas" among the

medical community. Nitrous oxide (N_2O) is also a byproduct of microorganisms when they metabolize molecules that contain nitrogen. Nitrogen is one of the major elements that makes up cellular life and is also a component of "**reactive nitrogen species (RNS)**," which are a collection of molecules that can be used to support growth and metabolism, but can also be toxic to cells in high concentrations. The microbial nitrogen cycle has three primary processes: **nitrogen fixation**, which is the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3); **nitrification**, which is the conversion of NH_3 to nitrate (NO_3^-); and **denitrification**, which is the conversion of NO_3^- back to N_2. Both nitrification and denitrification result in some emission of nitrous oxide because of the way microbial metabolisms and their enzymes evolved. However, the amount of nitrous oxide released by these two processes is dependent on the environment. The most important environmental determinants for nitrous oxide production are oxygen, the amounts of ammonia and nitrate available to microorganisms, and water availability. In general, environments with less oxygen, more ammonia, more nitrate, and more water produce the most nitrous oxide, namely because the enzymes that convert RNS to nitrous oxide are mostly active under these conditions.

The only biological removal mechanism for nitrous oxide is a group of microorganisms that have a unique ability to turn nitrous oxide back into nitrogen. These microorganisms become outnumbered and overwhelmed in ecosystems with low oxygen, high water content, and high nutrient (e.g. organic carbon, ammonia, nitrate) availability. The only other way that nitrous oxide is destroyed is through chemical processes, mostly once the gas reaches the atmosphere. Our best hope to stop the accumulation of nitrous oxide to the atmosphere is to control its production!



Microbial Nitrogen Cycle (BioRender). Note the nitrous oxide production during nitrification and denitrification.

3. ***How are humans changing the microbial cycles of methane and nitrous oxide?*** Both methane and nitrous oxide production are favored in environments with low oxygen, high water availability, and an abundance of nutrients that feed the microbes – namely organic carbon for methane production and ammonia/nitrate for nitrous oxide production. Landfills, rice paddies, and marshes are rich in organics and generally anoxic, supporting the grown and activity of methanogens.

Furthermore, the cow digestive system, or **rumen**, is loaded with methanogens. Methane from cow burps is considered a major source of human-caused methane, along with treatment (composting) of manure. Common agricultural practices – the application of anhydrous ammonium nitrate fertilizer and irrigation – ensure high water availability and high amounts of nutrients to support the growth and activity of nitrifiers and denitrifiers, along with their production of nitrous oxide. Municipal waste management and waste water treatment are other common sites where human-caused emissions of methane and nitrous oxide are high due to the favorable environmental conditions for the microbes in these engineered systems. By understanding the key environmental variables that increase methane and nitrous oxide production by microorganisms – oxygen, water, nutrients – we can identify both the environments and our societal practices that ought to be changed to promote greenhouse gas consumption and limit production.

4. ***What can be done to reset the balance of these cycles?*** The first step for any solution is to identify the problem. In the classroom, it is important to teach and learn: a) why and how microorganisms are important in cycling climate active gases, b) some of the key names of microorganisms and their processes that are involved in methane and nitrous oxide cycling, c) the environmental conditions that favor microbes and their processes that increase production of methane and nitrous oxide, and d) common places in and around our own towns, cities, landscapes, and beyond that maintain conditions that support microbes that generate methane and nitrous oxide. After identifying the problem, an example of solutions could include how to: a) change environmental conditions, b) engineer new systems, or c) change common practices, to prevent production – or promote consumption – of methane and nitrous oxide. Examples of learning guides and activities are listed below.

Relevance for Sustainable Development Goals and Grand Challenges
(https://sdgs.un.org/2030agenda)

The microbial cycling of greenhouse gases relates most closely to the following SDGs:

- **Goal 12. Ensure sustainable consumption and production patterns**. To rebalance the production-consumption cycling of climate-active gases, we must reconsider and devise new practices that: a) prevent the accumulation of organic material in anoxic, water-logged soils, b) vastly reduce the amount of fertilizer nitrogen applied to crops, and c) encourage the consumption, rather than production, of methane and nitrous oxide by natural microbial populations.

- **Goal 13. Take urgent action to combat climate change and its impacts.** Although carbon dioxide from fossil fuel combustion is still the focus for greenhouse gas mitigation, the unabated increase in methane and nitrous oxide is of growing concern. The problem is more nuanced due to the connections between our growing need for food and fuel with the effects of our practices on the vast microbial world that underlays Earth's ecosystems. Urgent action can be directed through educating ourselves about the connection between our lifestyles and practices with the microbes that control the cycling of climate-active gases. Creative solutions can only be devised with a keen understanding of the system.

Potential Implications for Decisions

1. ***Individual***
    - ***a.*** How do my food choices contribute to climate change? Is organic produce made with less fertilizer? How does a plant-based diet versus meat consumption (from low to moderate to heavy levels of consumption) influence greenhouse gas production? How can I find this information?
    - ***b.*** Where does my own waste go when I flush the toilet? Is the wastewater treatment facility and municipal waste facility aware of the methane and nitrous oxide that is emitted? What microbial processes are active in wastewater and municipal solid waste treatments? Does my city use a landfill? Does my city/township have policies to slow the production of these greenhouse gases?

2. ***Community policies***
    - ***a.*** Does the city audit greenhouse gas production from water and waste management facilities?

3. ***National policies***
    - ***a.*** Should food growers have economic incentives to reduce methane and nitrous oxide production?
    - ***b.*** Should we collectively work with other countries to slow methane and nitrous oxide release from landscapes that are changing due to climate change (e.g. thawing permafrost; ocean sediments; coastal oxygen minimum zones)

Pupil Participation

1. ***Class discussion***: where are some local environments that are supportive of methane and nitrous oxide production? How could you tell? How can the methane and nitrogen cycles be changed to promote consumption of these greenhouse gases and limit their production?

2. ***Pupil Stakeholder Awareness***: Can we, as citizens of our town/county/country, change policies or behaviors that will change the environmental conditions that influence microbial cycling of greenhouse gases? What roles do we as individuals, or family units, play in changing societal behaviors and systems to change these environments to a more balanced state in terms of greenhouse gas production?

The Evidence Base, Further Reading and Teaching Aids

Nitrogen cycle: http://archive.bio.ed.ac.uk/jdeacon/microbes/nitrogen.htm#Top
Soil Science Society of America: resources for K-12 educators https://www.soils4teachers.org/

Acknowledgements

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Glossary

Anoxic: an environment devoid of oxygen
Archaea: one of the three Kingdoms of life. Unicellular life-forms that possess unique molecular characteristics; often found in extreme environments (e.g. high temperature, high salt, acidic pH)
Climate Change: long-term change in the earth's climate due to an increase in the average atmospheric temperature. Exacerbated by increased emissions of greenhouse gases to the atmosphere.
Denitrification: a microbial process that involves the enzymatic reduction of nitrogen oxides (NOx) to dinitrogen (N_2); enzymes (reductases) process nitrogenous substrates in the order of: nitrate, nitrite, nitric oxide, nitrous oxide, dinitrogen
Fossil Fuels: combustable energy sources derived from the decomposition of buried life forms from millions to hundreds of millions of years ago
Greenhouse gas: a gas that absorbs and emits radiant energy within the thermal infrared range that, when in the atmosphere, causes the greenhouse effect
Methane: an organic molecule containing one carbon atom and 4 hydrogen atoms; the major component in natural gas
Methanogen: a group of specialized Archaea that grows by converting hydrogen gas and carbon dioxide into methane.
Methanotroph: a specialized group of bacteria that grow by oxidizing methane to carbon dioxide.
Nitrification: a microbial process in the nitrogen cycle that oxidizes ammonia (from nitrogen fixation) into nitrogen oxides (nitrite and nitrate). This is a process that requires O_2.
Nitrogen fixation: a microbial process that fixes dinitrogen (N_2) into ammonia (NH_3), which is a required nutrient for all cellular life.
Nitrous oxide: a nitrogen oxide (N_2O) gas that has about 300 times the heat-holding capacity as carbon dioxide in the atmosphere; produced by nitrification and denitrification; a.k.a. laughing gas used as an anesthetic in dentistry.
Reactive Nitrogen Species (RNS): nitrogen-containing molecules that can be used or metabolized by cellular life and is toxic in high concentrations; the production and consumption of RNS is completely reliant on the activity of microorganisms.
Rumen: specialized stomach compartment in ruminants (e.g. cows) for the digestion of plant material; reliant on the activity of microorganisms including methanogens; source of methane by cows.