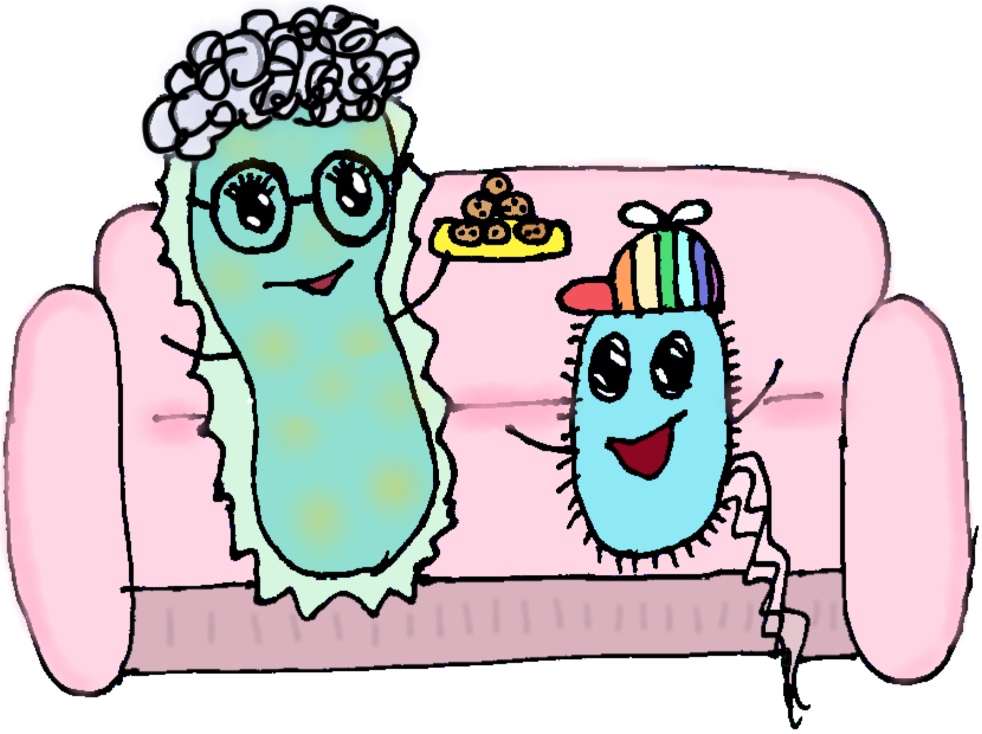
Living on Thin Air

Timmy: Granny, you tell me when I am not hungry that I must be living on thin air: is this possible?



Zahra Islam[1,2] and Chris Greening[1]

[1]Department of Microbiology, Biomedicine Discovery Institute, Monash University, Melbourne, Australia, [2]STEM College, RMIT University, Melbourne, Australia

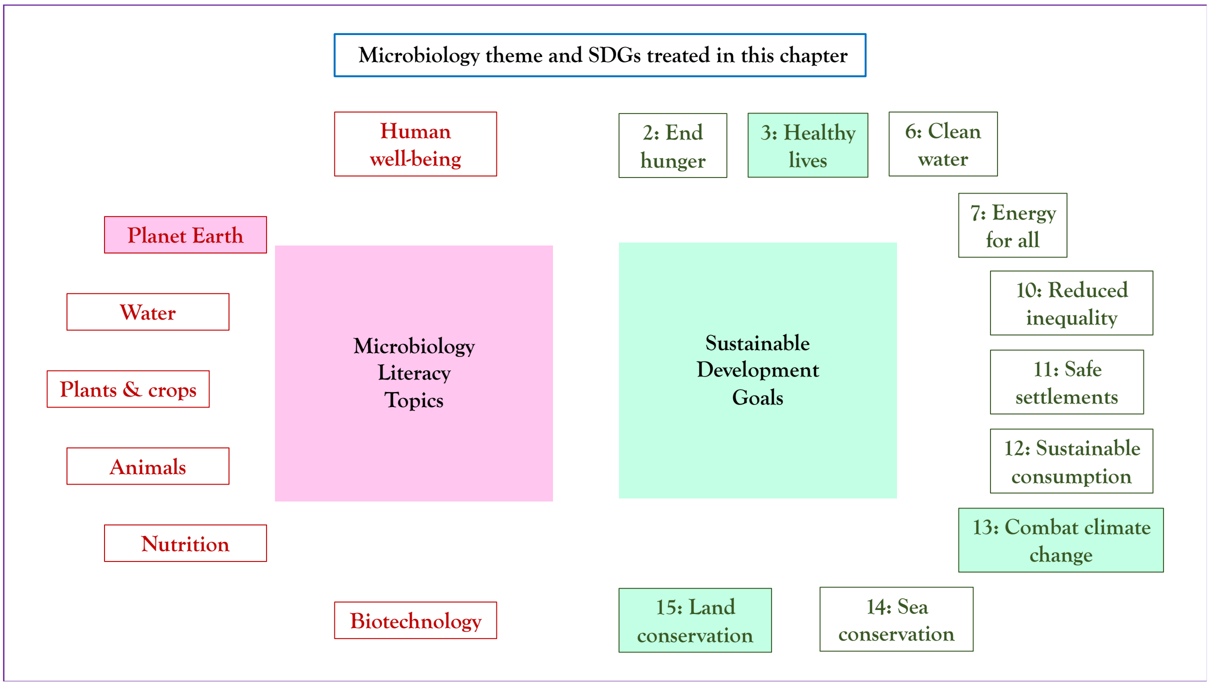
Living on Thin Air

Storyline

What would you do if you suddenly had no access to food? We can endure for long periods by breaking down fats and other energy reserves, but can't survive more than a couple of months of starvation. Some have bizarrely claimed we can live solely on thin air – a process coined breatharianism – but this of course has proven deadly. Yet many bacteria can survive literally for many years, likely millennia, without food. It's recently been shown that many of these bacteria do this by literally living on air: they continually consume the tiny amounts of three gases from the atmosphere, namely hydrogen, carbon monoxide, and methane. These gases allow bacteria to survive indefinitely in dormant states, akin to hibernation, and may even allow some specialist organisms to grow. There is increasing evidence to suggest that trace gas consumers are the norm, rather than exception, in global soil and marine ecosystems. Moreover, trace gases help bacteria live in some of the most extreme environments on Earth, ranging from the frozen deserts of Antarctica to the deepest depths of the ocean to the acidic craters of volcanoes. By consuming these gases, these bacteria also help regulate the composition of the atmosphere and mitigate emissions of greenhouse gases. So while we can't live on air, it turns out breatharians do live among us after all!

The Microbiology and Societal Context

The microbiology: microbial nutrition; microbiomes; extreme environments; metabolic flexibility; biodiversity; plant, animal and human health. *Sustainability issues*: atmospheric pollution; greenhouse gases; environmental management.



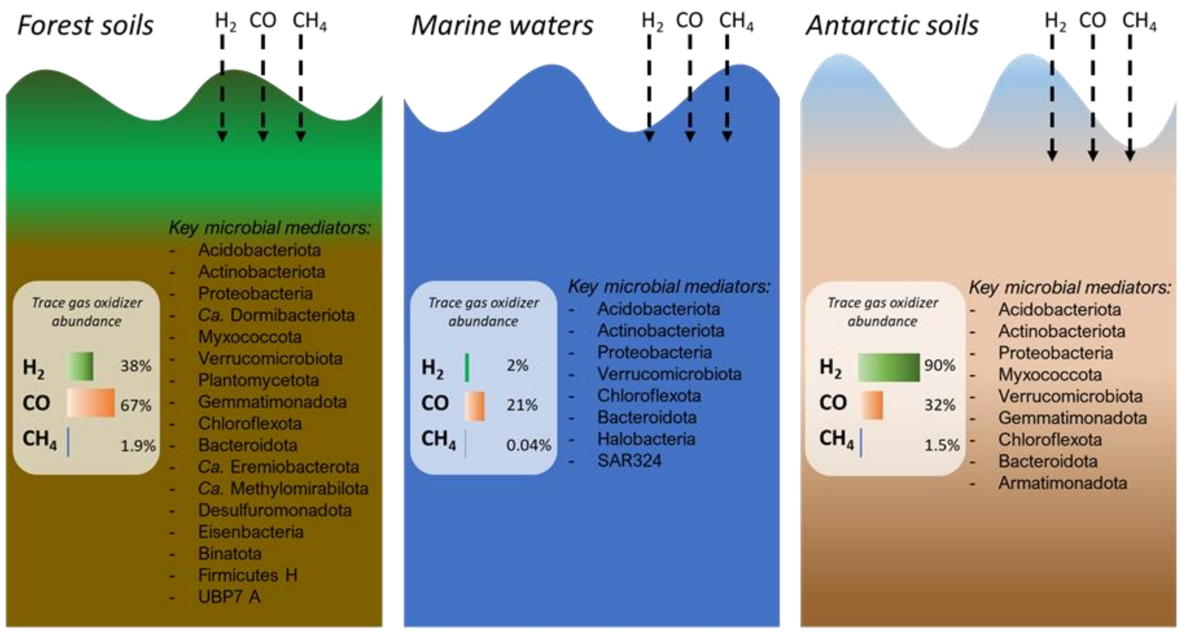
Living on Thin Air: The Microbiology

1. Bacteria enter dormant states when starved of their preferred food sources. Bacteria are numerous and diverse in harsh ecosystems such as deserts, volcanic craters, and deep oceans. These environments are likely devoid of primary producers (organisms such as plants that are at the base of the food web and provide food for all other organisms), experience fluctuations in nutrient availability, and have harsh abiotic characteristics that require bacteria to develop numerous survival strategies. It can be a tough ask for bacteria to grow in such environments, but their resident microbes are still able to survive for long periods. To do so, they often enter a state of dormancy, much like how a bear hibernates during winter. In this state, bacteria generally miniaturize or form hardy structures (e.g. spores) to withstand environmental stresses, while vastly reducing their energy expenditure. This adaptation is critical for bacteria to survive in the extreme environments discussed. However, even in relatively nutrient-rich soils and waters, bacteria also often are forced to enter dormant states due to intense competition from other microorganisms. In dormant states, bacteria still require some energy for basic purposes such as repair of injuries (metabolic, physical). Where do they get this? Like us, bacteria can survive for long periods by consuming energy reserves like fat stores. In addition, it's become apparent that many previously characterized fussy eaters are actually more open to trying new foods than previously thought.

2. Bacteria consume atmospheric energy sources to survive starvation. The atmosphere is critical for life in various ways: as the source of oxygen for respiration, carbon dioxide for photosynthesis, and nitrogen that is fixed for plant growth. Yet in recent years, it's become apparent that the atmosphere is a hidden reservoir of energy too. Three high-energy gases, namely hydrogen (H_2), carbon monoxide (CO), and methane (CH_4), are present in low concentrations throughout the atmosphere. While humans cannot use these gases, bacteria have evolved special enzymes to use these gases as energy sources for aerobic respiration. These gases are highly dependable energy sources for long-term survival given they are continually present, freely diffuse into cells, and yield much energy when oxidized. Indeed, with the atmosphere so vast, there's plenty of gas to around and so little need for bacterial fighting! While hydrogen, carbon monoxide, and methane are all naturally present in the atmosphere, human activities such as fossil fuel combustion and agricultural practices have resulted in vast increases in their emissions. This is problematic given methane is a climate active and carbon monoxide is highly toxic. These bacteria therefore provide a key ecosystem service by removing significant amounts of these gases from the atmosphere.

3. Hydrogen isn't just a fuel source for future vehicles. Molecular hydrogen is a major but overlooked energy source for bacteria. Just as with hydrogen-powered vehicles, microbial cells can react hydrogen with oxygen to release much energy; the only exhaust is water. We know environments with naturally higher amounts of hydrogen, such as wetlands, geothermal hot springs, or the human gut, are often inhabited by bacteria that can grow on hydrogen alone. However, it was only recently discovered that bacteria in numerous other environments – spanning soils, waters, plants, buildings, and potentially even the atmosphere itself – live by consuming atmospheric hydrogen. To do so, they use special enzymes called **hydrogenases** to bind and oxidize hydrogen under the prevailing conditions. Collectively, soil bacteria account for about 75% (60 million tonnes) of the hydrogen lost from the atmosphere each year and hence keep levels of this climate-relevant gas in check. Atmospheric hydrogen consumption appears to be a general strategy: as summarized in the cartoon below, at least nine different bacterial phyla have been experimentally shown to consume atmospheric hydrogen and numerous others are genetically capable of this process. But why do so many bacteria use this gas? Genetic experiments focused on two well-known Actinobacteria, *Mycobacterium* and *Streptomyces*, show that cells only consume hydrogen during dormancy when their preferred organic foods are limited. Mutant cells that lack the hydrogenases that mediate this process have greatly reduced long-term survival. Yet other bacteria, for example the mine-associated species *Acidithiobacillus*, use hydrogen to give themselves a growth boost when growing on tough substrates such as iron.

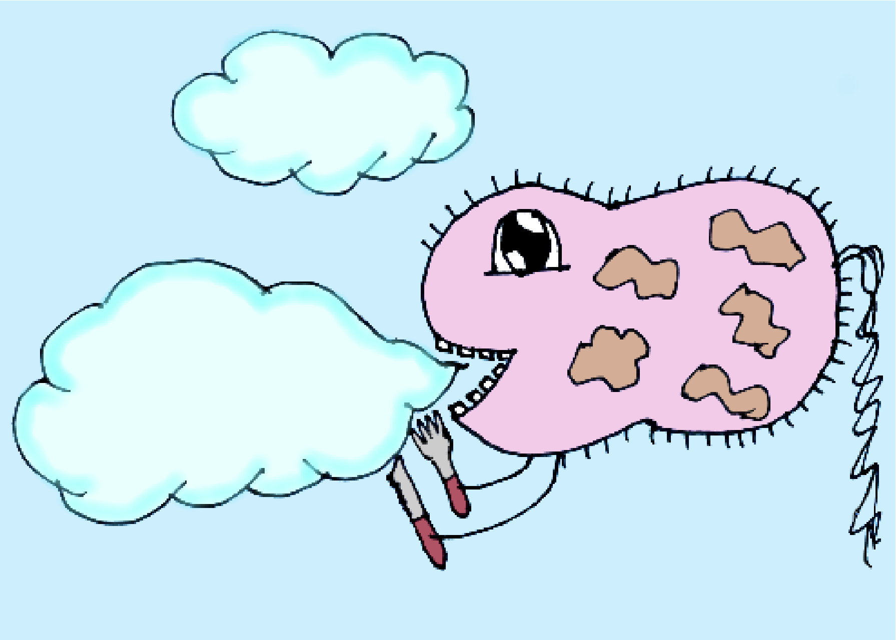
4. Carbon monoxide is toxic for us, but can be delicious for microbes. If you've ever created a campfire, chances are that you inadvertently added some carbon monoxide into the atmosphere. This gas is acutely toxic to us and is a key reason why indoor and outdoor air pollution kills millions per year. Yet numerous bacteria and archaea depend on this gas as an energy source. To do so, they convert carbon monoxide into carbon dioxide using the enzyme carbon monoxide dehydrogenase, and use the energy derived for aerobic respiration. Moreover, some bacteria can fix the carbon dioxide produced through this process to make biomass. Bacteria that grow on elevated levels of carbon monoxide are well-understood, but only recently has the potential benefits of using only atmospheric concentrations of carbon monoxide been investigated. Similarly to hydrogen, many bacterial and some archaeal species can consume atmospheric carbon monoxide, primarily as a mechanism to support long-term survival. In fact, current models of atmospheric carbon monoxide oxidation have shifted from a growth-centric to survival-centric one, given that so many microbes appear to use this gas for long-term survival. Together, they consume 10% (250 million tonnes) of the carbon monoxide lost from the atmosphere each year and efficiently counteract our emissions, such as from vehicle exhausts.



Summary of key microbial mediators of atmospheric trace gas oxidation in forest soils, marine waters and Antarctic soils. The concentrations of hydrogen (H_2), carbon monoxide (CO) and methane (CH_4) in the atmosphere are 0.53, 0.1 and 1.77 parts per million by volume (ppmv), respectively. Adapted from Greening and Grinter, Nature Reviews Microbiology 2022.

5. Bacteria partially alleviate emissions of the greenhouse gas methane. Increases in global methane concentrations are responsible for approximately a third of global warming. Solutions are desperately needed to reduce emissions of this greenhouse gas to the atmosphere or alternatively 'mop up' the gas already present in the atmosphere. Could bacteria be the answer? Various bacteria and archaea consume the excess methane present in different environments, for example hydrothermal vents and landfill sites, thereby reducing emissions into the atmosphere. However, bacteria capable of consuming the methane already present in the atmosphere tend to be rare community members in soils (<1% of bacteria). This reflects the fact that methane oxidation is a relatively complex process that requires a high oxygen supply and various rare metals. Nevertheless, while atmospheric methane oxidizers are not as abundant as either hydrogen or carbon monoxide oxidizers, they still play an important role in removing methane from the atmosphere, accounting for 4% (28 million tonnes) of the atmospheric methane lost each year. More research is needed to understand what factors restrict atmospheric methane oxidizers in soils and whether land management changes can stimulate this important ecosystem service.

6. Some bacteria can grow using atmospheric energy sources alone. Classically, it's been thought that atmospheric trace gases are too dilute to be able to support growth. Yet this is based on the outdated assumption that bacteria only grow by using one energy source, or gas substrate, at a time. A 2019 study revealed a globally abundant lineage of soil bacteria, called *Methylocapsa*, are in fact capable of growth using only trace gases. To do so, they simultaneously consume atmospheric methane, hydrogen, and carbon monoxide to meet its energy needs for growth. This process of growing on multiple energy sources at one time is called **mixotrophy**. This lifestyle has enabled this bacterium to adapt to a wide range of environments, from pasture soils to tropical termite mounds to polar permafrost. Now that we've found one bacterium capable of living solely on air, we suspect that there may be more with that special ability.



Time for dinner!

7. Some ecosystems appear to be primarily driven by atmospheric energy sources. Most ecosystems are directly or indirectly driven by solar energy that support plants and other photosynthetic primary producers. Geologically-powered ecosystems, for example hydrothermal vents, are an important exception; here chemosynthetic bacteria grow on the geological gases continually seeped and support complex ecosystems. Yet in recent years, it has emerged that some extreme ecosystems may be primarily driven by atmospheric energy. In Antarctic deserts, where ultradry soils, freezing temperatures, and polar winters exclude plants and most photosynthetic microorganisms, the major primary producers present appear to be trace gas oxidizers. Various bacteria, especially from the lineage Actinobacteria, can use atmospheric hydrogen and carbon monoxide to both meet energy needs and fix carbon dioxide into biomass. Moreover, these bacteria use the water derived from hydrogen oxidation to continually stay hydrated. It's probable that these unusual primary producers support various other microbes present, as well as more complex organisms such as springtails. Other primarily atmospherically-driven ecosystems may potentially exist where photosynthetic bacteria are excluded, for example caves, mountaintops, other deserts, and potentially the atmosphere itself.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 13 – Combat climate change:** Trace gas oxidizers, especially those in soils, directly influence the composition of the atmosphere. They consume a substantial fraction of the climate-active gas methane released to the atmosphere each year. In addition, they greatly moderate the levels of atmospheric hydrogen and carbon monoxide in the atmosphere, leaving more free hydroxyl radicals available to reduce methane levels. Increasing global emissions due to human activities may lead to a shift in the abundance of bacterial species able to maintain a stable equilibrium of these gases within the atmosphere. There may be potential to use land management practices to stimulate atmospheric methane removal.
- **Goal 15 – Land conservation:** Trace gas oxidizers play a key role in supporting the health of various ecosystems. They help sustain the biodiversity of global soil ecosystems, enable the productivity of extreme environments such as Antarctic soils, and mediate numerous ecosystem services. Yet increasing emissions of hydrogen (through a hydrogen economy) and methane (through agricultural activities) has potential to change their abundance and activities. A deeper understanding of the relationship between the atmosphere and biosphere is needed to predict how local and global change will affect these microorganisms.
- **Goal 3 – Healthy lives:** Several human, animal, and plant pathogens can consume atmospheric hydrogen or carbon monoxide. Most notably, the causative agent of tuberculosis (*Mycobacterium tuberculosis*) can consume carbon monoxide. This may contribute to the notorious survival of this pathogen in human lungs and may contribute to the increased susceptibility of cigarette smokers to tuberculosis.

Pupil participation

1. ***Discussion topic*:** Class discussion on what sorts of environments bacteria can live in if the only food they need is air.

2. ***Pupil stakeholder awareness*** (questions to ask)

   a. Do you think it would be possible for humans to live on thin air? Why? Why not?
   b. Should we be engineering bacteria to consume methane to combat climate change?
   c. Could the atmospheres of other planets also support microbial life?

3. ***Exercises***
   a. Describe the composition of the atmosphere. Of the gases present, which are important for life and why?
   b. How can understanding which atmospheric trace gases can be used by bacteria be used to fight climate change?
   c. Do bacteria influence the Earth's atmosphere?

The evidence base, further reading and teaching aids

Antarctic bacteria live on air and make their own water using hydrogen as fuel:
https://theconversation.com/antarctic-bacteria-live-on-air-and-make-their-own-water-using-hydrogen-as-fuel-171808
Breatharian bacteria breakdown greenhouse gases and toxic pollutants:
https://www.monash.edu/discovery-institute/news-and-events/news/2021-articles/breatharian-bacteria-breakdown-greenhouse-gases-and-toxic-pollutants
Toxic for most, an energy source for others – researchers discover microbes take advantage of carbon monoxide: https://www.monash.edu/science/news/current/toxic-for-most,-an-energy-source-for-others-researchers-discover-microbes-take-advantage-of-carbon-monoxide
Bacteria ate up all the methane that spilled from the Deepwater Horizon well:
https://www.nationalgeographic.com/science/article/bacteria-ate-up-all-the-methane-that-spilled-from-the-deepwater-horizon-well
Microbes in trees eat methane for breakfast:
https://www.youtube.com/watch?v=qJqnOsCWG_A
Hydrogen-breathing aliens? Study suggests new approach to finding extraterrestrial life.
https://theconversation.com/hydrogen-breathing-aliens-study-suggests-new-approach-to-finding-extraterrestrial-life-137630
Greening, C. and Grinter, R. (2021), *Microbial oxidation of atmospheric trace gases*, invited article for Nature Reviews Microbiology
Greening, C., Islam, Z. F. & Bay, S. K. (2021), *Hydrogen is a major lifeline for aerobic bacteria,* Trends in Microbiology, available online 27 August 2021.

Glossary

Aerobic respiration – production of usable energy (ATP) through the breakdown of energy sources (e.g. hydrogen) using oxygen
Carbon fixation – the conversion of carbon dioxide gas into organic carbon by chemosynthetic and photosynthetic primary producers
Carbon monoxide dehydrogenases – enzymes that catalyze the reversible oxidation of carbon monoxide with water to carbon dioxide, protons and electrons
Chemosynthesis – Conversion of carbon dioxide into biomass using chemical compounds (e.g. hydrogen or sulfur) as the energy source
Climate active – gases that contribute to global warming, such as methane and carbon dioxide

Dormancy – the period in an organism’s life cycle where growth and replication have been temporarily halted
Ecosystem service – benefits provided to humanity by ecosystems, including microorganisms
Hydrogenases – metalloenzymes that reversibly cleaves molecular hydrogen into protons and electrons
Metabolism – the complete set of life-sustaining chemical reactions within an organism
Metabolic flexibility – the ability of a bacterium to use more than one energy source or nutritional strategy
Methane monooxygenases – enzymes that catalyze the reaction between methane and oxygen to produce methanol
Mixotrophy – the process by which an organism can use multiple energy sources simultaneously for growth or survival
Photosynthesis – Conversion of carbon dioxide into biomass using sunlight as the energy source
Primary producer – an organism that can fix carbon dioxide to produce biomass either photosynthetically or chemosynthetically