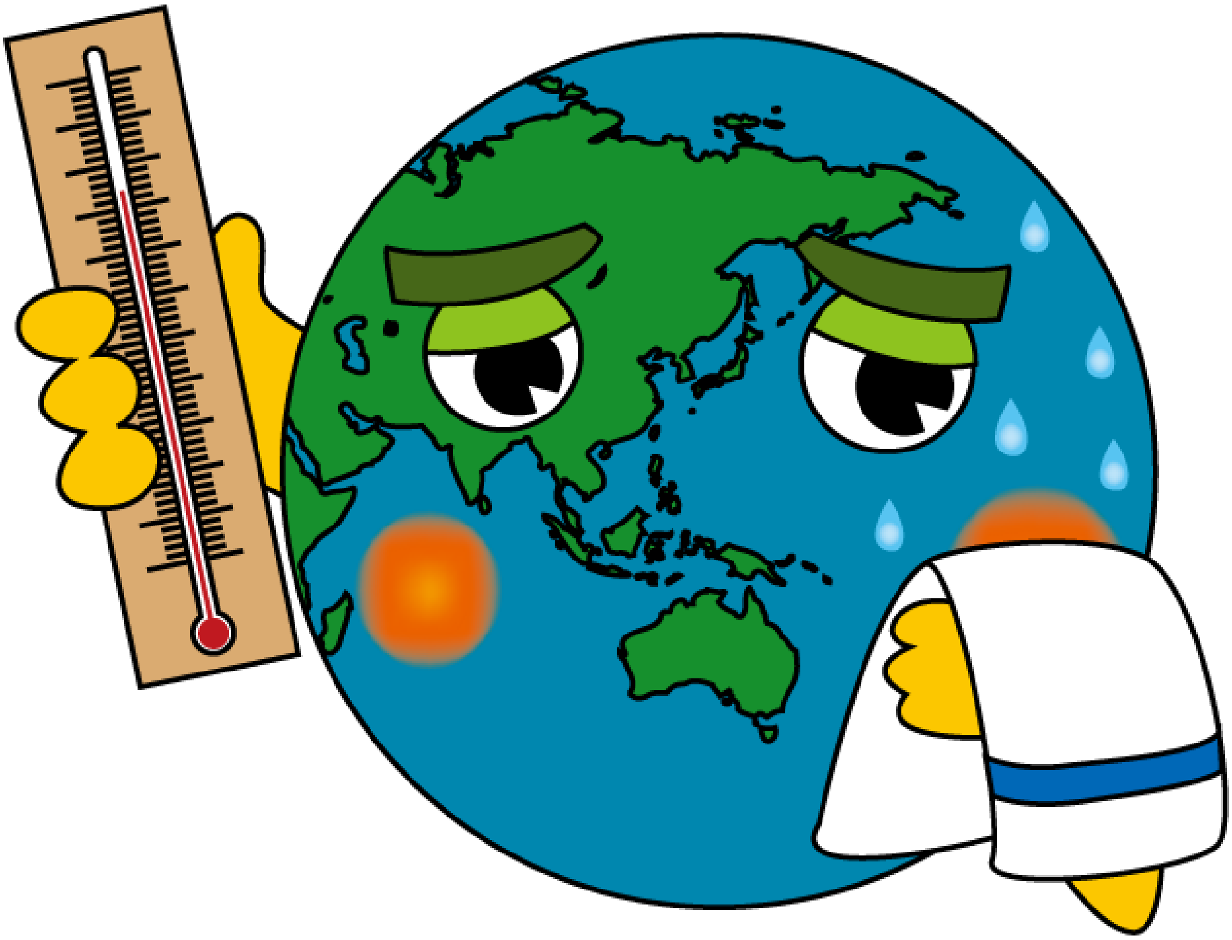
Agriculture, greenhouse gases and global warming

Daddy: I really would like a hamburger at the bowling alley this afternoon, but Jenny told me yesterday that cows contribute to global warming: is this true?



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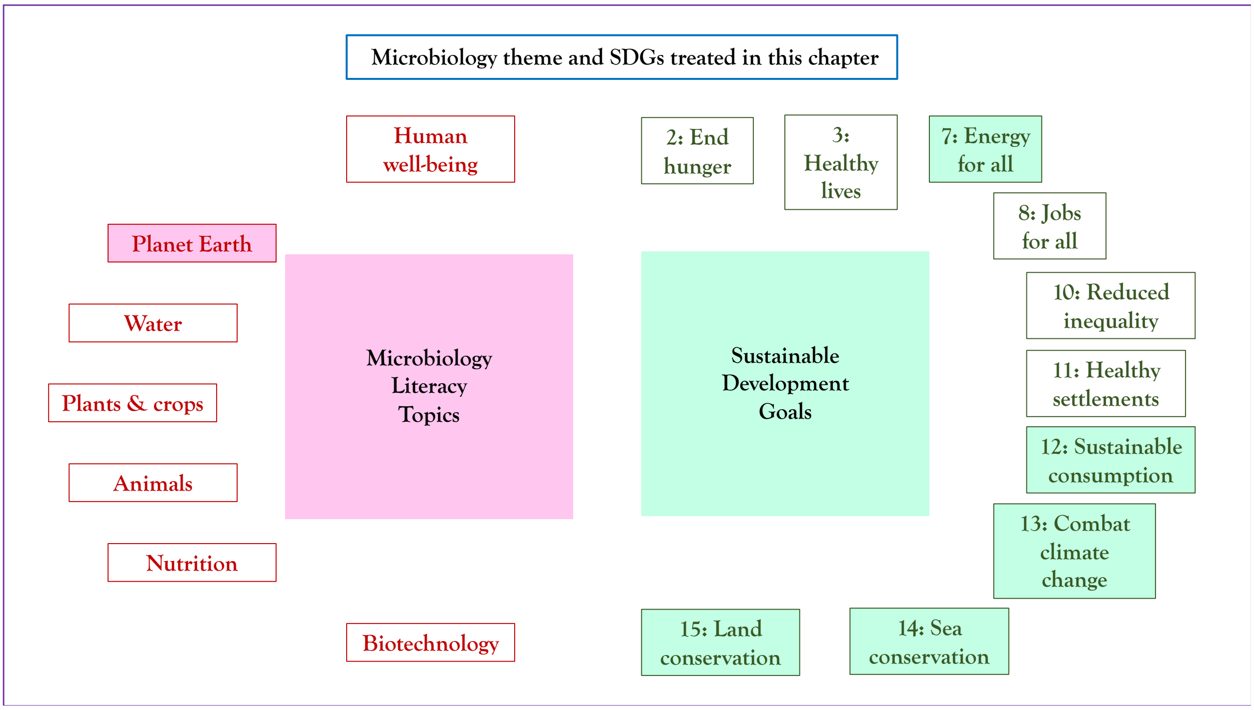
Greenhouse Gases, Agriculture, Microbes and Global Warming

Storyline

Global climate change due to an increase in the concentration of greenhouse gases in the atmosphere is presently one of the most important environmental problems. Methane (CH_4) and carbon dioxide (CO_2) are among the main greenhouse gases. The greenhouse effect of the CH_4 molecule is 28 times higher than that of the CO_2 molecule. Most of the methane released into the atmosphere is of biological origin. Methane is generated in various terrestrial ecosystems by specialized microorganisms – methanogenic archaea – which develop as part of an anaerobic microbial community that decomposes complex organic substances. Methane is the end product of organic decomposition, and different compounds can serve as the main substrates for methanogens in different ecosystems. Studying the formation of methane and its effect on climate as a greenhouse gas is associated with a systems approach and thinking. The relationships of microorganisms that form methane and its connection to global ecology allows us to consider interactions in biological systems at various levels of their organization as well as their interdependence.

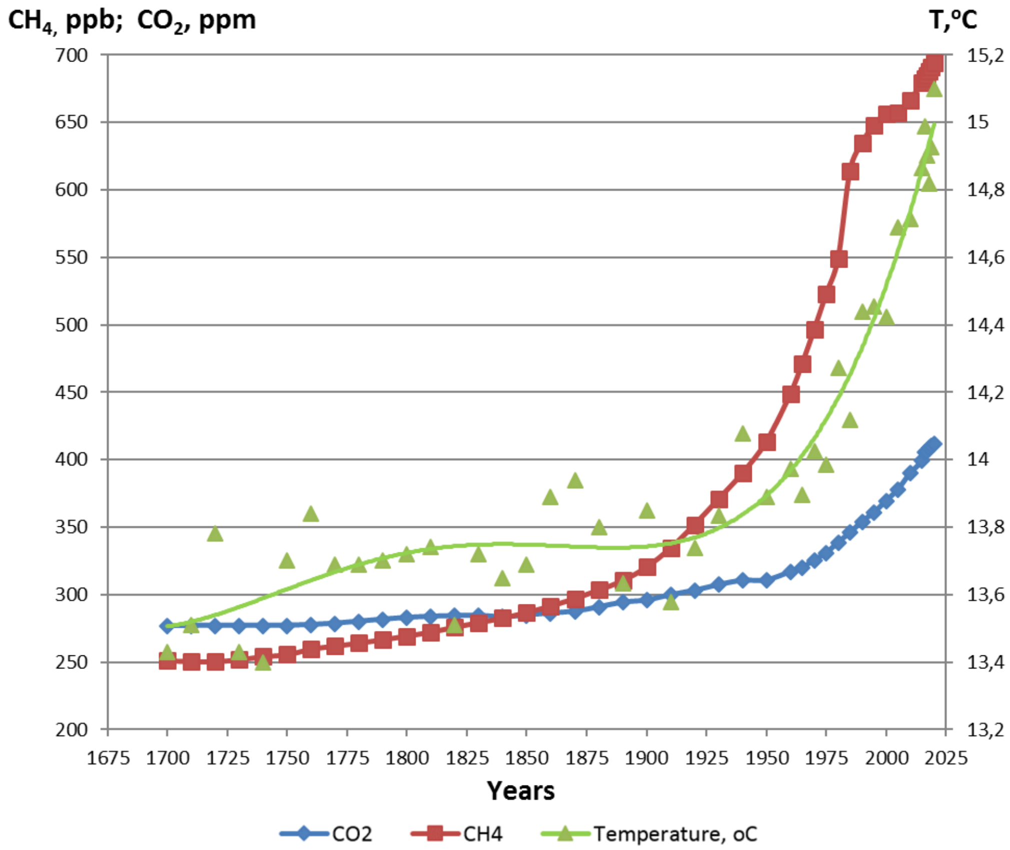
The Microbiology and Societal Context

The microbiology: microbial greenhouse gas production; methane emissions: carbon dioxide emissions; anaerobic microbial community; methanogens; methanotrophs; wetlands; landfills; rice fields; ruminants; waste water treatment; intensive farming and animal husbandry. *And, peripherally for completeness of the storyline:* industrial development; economics planning. *Sustainability issues:* global warming; green ecology; food and energy, biogas production; environmental pollution.



Greenhouse gases, Agriculture, Microbes and Global Warming: the Microbiology

1. The greenhouse effect. Most of the sun's rays penetrating the atmosphere do not interact with it, i.e. the atmosphere does not heat up. But the Earth's surface does absorb solar radiation, and thereby heats up. A heated body emits infrared radiation. Such radiation from the Earth's surface is absorbed in certain spectral regions by optically active or "greenhouse" gases, and therefore the atmosphere heats up, which causes the subsequent heating of its underlying surface (soil, ocean). Thus, changes in the concentration of greenhouse gases in the atmosphere lead to an increase in the Earth's temperature and change the energy balance of the climate system (https://www.youtube.com/watch?v=BPJJM_hCFj0).



Increase in atmospheric concentrations of methane and carbon dioxide and the average temperature of the Earth over the past few centuries.

2. Greenhouse gases. The main greenhouse gases are: water vapor (H_2O), which make up clouds, carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrogen oxides (N_2O, etc.) and various halogenated carbon compounds, mainly freons used as refrigerants, propellants in aerosols, and blowing agents in the production of polyurethane foam and expanded polystyrene.

Before humankind began to actively develop industry, the main sources of greenhouse gases were evaporation from the surface of the World Ocean, volcanic activity and forest fires, as well as natural soil and bog ecosystems.

Since the beginning of the industrial era, greenhouse gases have been released into the atmosphere from fossil fuels (carbon dioxide), rice growing and oil extraction (methane), refrigerant leaks and the use of aerosols (fluorocarbons), rocket launches (nitrogen oxides), and automobile engines (ozone). In addition, human industrial activity has led to a reduction in the area occupied by forests - the main natural sinks of carbon dioxide. The beginning of an increase in the concentration of CO_2 and methane and an increase in the average temperature of the Earth coincides with the approximate beginning of the industrial era of human development.

3. Increasing greenhouse effect affects global environmental processes. Due to thermal expansion of water and melting of glaciers, global mean sea level is rising at an average rate of 3.1 mm/year. Significant increases in precipitation are noted in the eastern parts of the North and South Americas, northern Europe, and northern and central Asia. At the same time, precipitation is decreasing in the Sahel, the Mediterranean, southern Africa and parts of South Asia. In terrestrial ecosystems, an earlier onset of spring phenomena and shifts in the habitable ranges, and hence distribution areas, of plant and animal species, directed towards the poles, occur, which is associated with warming. In some marine and freshwater systems, shifts in the habitat and abundance of algae, fish and plankton are associated with increases in water temperature, as well as changes in ice cover, salinity and oxygen content. There are also other phenomena that contribute to the intensification of the global greenhouse effect.

4. Sources of greenhouse gases are natural and anthropogenic ecosystems. Water vapor is the main natural greenhouse gas and is responsible for 60% (and even more by some estimates) of the greenhouse effect on the Earth.

The second largest contributor to the greenhouse effect is carbon dioxide. The main sources of release of carbon dioxide to the atmosphere are of anthropogenic origin, such as the burning of fossil fuels; combustion of biomass, including forest biomass; and some industrial production.

Significant emission of carbon dioxide occurs during agricultural activities. Intensive tillage using a plow leads to aerobic microbial oxidation of soil organic matter (SOM) to carbon dioxide and water.

The main sources of methane are both natural (wetlands) and anthropogenic (domestic ruminants, landfills, rice fields) ecosystems.

Most of the greenhouse ozone is formed in the atmosphere as a result of chemical reactions involving various volatile organic compounds: nitrogen oxides, carbon monoxide (CO), etc. in the presence of oxygen, water vapor and sunlight. Transport, industrial emissions, and some chemical solvents are the main sources of these substances in the atmosphere. Methane also contributes to the formation of ozone.

Agriculture is the main source of increasing levels of nitrogen oxides in the planet's atmosphere. Additionally, these gases are released during the decomposition of organic matter in the processes taking place at landfills and during wastewater treatment, as well as in some industrial productions.

Fluorinated gases are released into the atmosphere from leaks of refrigerants, as well as from a number of industrial processes.

Despite the fact that water vapor is the main greenhouse gas, international experts dealing with the problem of global climate change usually take into account only those gases, the increase in the concentration of which in the atmosphere is associated with anthropogenic impact on the biosphere. Of these, carbon dioxide and methane attract the main attention, since their concentrations in the atmosphere have increased significantly in the last century, in direct relation to human activities.

However, an increase in the concentration of the main anthropogenic greenhouse gases indirectly affects the concentration of water vapor in the atmosphere. As the Earth's temperature rises, evaporation increases and, consequently, the total concentration of water vapor also increases, which in turn enhances the greenhouse effect. On the other hand, increased humidity contributes to increased cloudiness. Since clouds in the atmosphere reflect the direct sunlight, it reduces the greenhouse effect.

Gas	Formula	Contribution to the greenhouse effect (%)	Contribution to the greenhouse effect (%) excluding water vapor
Water vapor	H_2O	60	-
Carbon dioxide	CO_2	24	60
Methane	CH_4	6	15
Halogenated gases	(H, C, F, Cl, Br, S, N) in the molecule	4,8	12
Ozone	O_3	3,2	8
Nitrogen oxides	N_2O, N_xO_y	2	5

The main greenhouse gases of the Earth's atmosphere and their average contribution to the greenhouse effect.

The main sink of carbon dioxide is its absorption by plants during photosynthesis, which use it as a carbon source.

The main sink of methane is abiotic (photochemical reactions in the atmosphere). Among the biological sinks of CH_4, the most important one is its consumption by aerobic soil microorganisms.

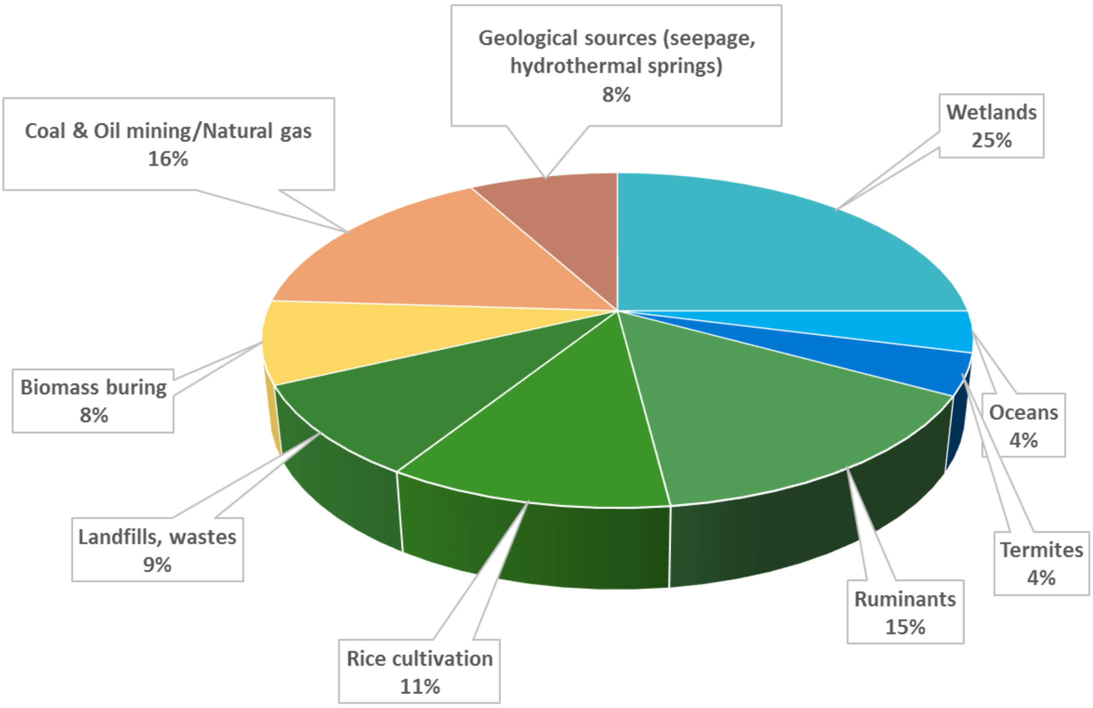
5. An important feature of methane as a greenhouse gas is its predominantly microbiological origin. The greenhouse effect of the CH_4 molecule is approximately 28 times greater than that of CO_2 molecule, but because its concentration in the atmosphere is much lower, it is considered to be only the second most important greenhouse gas after carbon dioxide. However, the concentration of methane is constantly increasing, so its ecological significance as a greenhouse gas is increasing too. Therefore, it is very important to study its sources and sinks, as well as the mechanisms of its formation in various ecosystems.

Under anaerobic conditions (in wetlands, rice fields and other waterlogged soils, in the intestines of ruminants and termites), methane is formed as a result of the activity of the methanogenic microbial community.

The main anthropogenic sources of methane are agriculture (rice growing) and animal husbandry (increasing livestock numbers). An additional contribution is a result of an increase in pastures and combustion of biomass (during the burning of forests, and of using wood for heating, the access of oxygen to the combustible material is often limited such that, in addition to complete oxidation to CO_2, the pyrolysis process begins to play a significant role, the product of which, among others, is methane).

Leaks during the mining of coal and natural gas deposits, as well as the emission of methane as a component of biogas formed at landfills, also make a contribution to the methane fluxes to the atmosphere. Finally, some geochemical processes are also responsible for methane emissions.

The main process of methane formation in both natural and anthropogenic systems is the microbial decomposition of complex organic compounds.



Contribution of various CH_4 sources to total methane emissions to the atmosphere. Shades of blue - microbial production of methane of natural origin, shades of green - microbial production of methane of anthropogenic origin, shades of red - geological sources of methane, yellow - thermochemical source of methane.

6. Microbiological formation and consumption of methane occurs with the participation of various groups of microorganisms. The microorganisms involved in the formation of methane (methanogenic archaea) are anaerobes; in the presence of oxygen, methanogenesis stops. In contrast, microbial oxidation of methane occurs with the participation of oxygen. In wetlands, although surface water is oxygenated, microbial activity in sediments exhausts oxygen below the sediment surface and creates an anaerobic environment. Methane is formed as a result of anaerobic degradation of organic matter in the sediment.

Because it is a gas, methane rises through the sediment until it reaches the surface and oxygenated water where it may be oxidized by aerobic methanotrophic bacteria – methane consumers – the main component of the so-called bacterial filter - a community of aerobic bacteria that intercepts metabolic products of anaerobic microorganisms rising from lower depths.

Microbial processes of methane formation and oxidation constitute the methane cycle. If all the methane generated in the anaerobic zone is absorbed by the bacterial filter, then the methane cycle is closed. This situation often occurs in slightly boggy forests and some wetlands. However, in many types of wetlands, part of the methane passes through the bacterial filter and enters the atmosphere (you can often see it bubbling from the surface of stagnant water; https://www.youtube.com/watch?v=YegdEOSQotE&t=1s), where it can further participate in various photochemical reactions and contribute to the greenhouse effect.

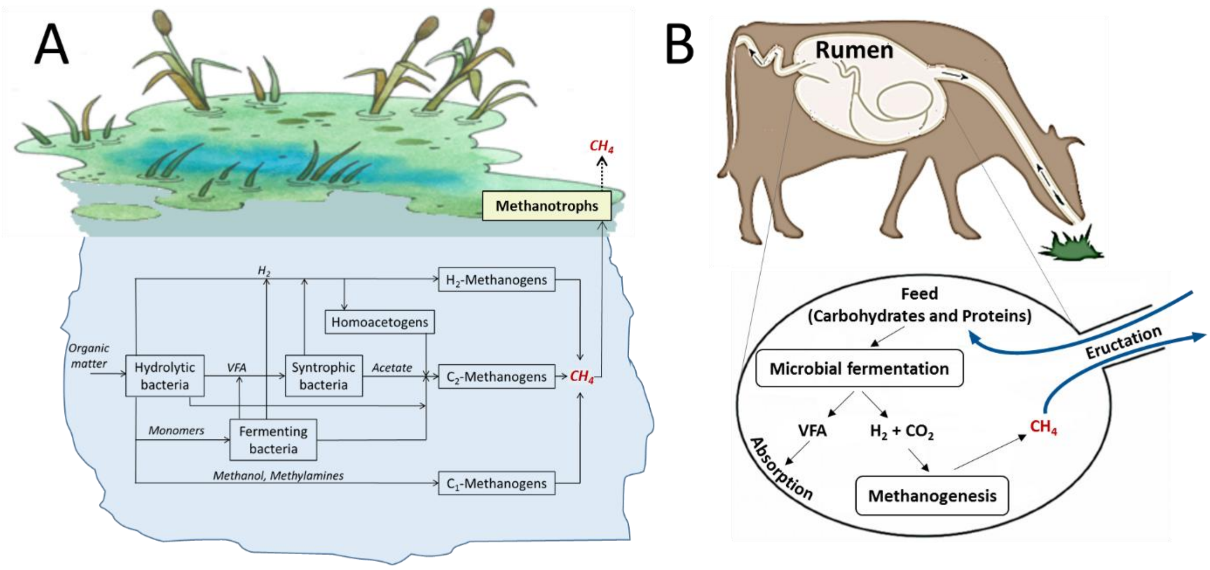
The activity of communities is regulated by various environmental factors such as temperature, pH, Eh, the concentration of oxygen and mineral elements, the availability of organic substrates, etc. Since the communities of methanogens and methanotrophs are spatially separated, their regulation by the aforementioned factors can occur quite independently. Thus, temperature conditions that directly affect the rate of metabolic processes can differ significantly on the surface and in deep layers of soil, peat and sediments of water bodies, and these differences can vary depending on the season. Accordingly, the outcome of the methane cycle will also vary.

7. The methane-producing anaerobic microbial community is an excellent example of a complex biological system. Its key components are various microbial groups closely related to each other by trophic (feeding) interactions (the transfer of carbon and energy between different members of the food web). Complex organic substances decompose in such a community in stages - the products of one microbial group are substrates for another, as a result of which the total energy of decomposed polymer compounds is redistributed between various microbial groups in the community on the basis of mutually beneficial cooperation between all microorganisms of the community.

So, for example, in wetlands and most other anaerobic ecosystems, the scheme of sequential decomposition of organic matter is as follows. Cellulose (the main component of plant debris) is broken down by extracellular enzymes of hydrolytic microorganisms with the release of glucose molecules, which are then consumed by the same hydrolytics, as well as by a large group of microorganisms that carry out various types of fermentation. The main products of the fermentation of glucose, as well as other saccharides and amino acids, the degradation products of proteins, which can also be present in the system and decomposed in parallel to the main metabolic pathway, are volatile fatty acids (VFA), as well as hydrogen and carbon dioxide. Various VFAs are degraded to acetate as a result of syntrophic microbial reactions, after which simple organic compounds remain in the anaerobic system, being substrates for terminal microorganisms.

In the vast majority of cases, methanogens are the terminal microbial group of the anaerobic community and produce methane as one of the final (together with CO_2) products.

In the trophic chain of the anaerobic microbial community, methanogens are represented by three groups: hydrogen-consuming (with CO_2 as a carbon source and electron acceptor), acetate (C2)-degrading (acetoclastic), and simple one-carbon (C1) compound-consuming (methylotrophic). In freshwater terrestrial ecosystems, including wetlands and waterlogged soils, the main trophic groups of methane-forming archaea are acetoclastic and H_2-consuming methanogens.



Formation of methane in wetland ecosystems (A) and in the gastrointestinal tract of ruminants (B). VFA (volatile fatty acids, mainly acetate, propionate and butyrate).

The main predominant families of methanogens in wetlands are *Methanomicrobiaceae*, *Methanobacteriaceae*, and *Methancoccaceae* and, relatively recently discovered, acid-tolerant methanogens of the family *Methanoregulaceae*, which perform a hydrogen-dependent pathway for methane synthesis, as well as acetoclastic methanogens of the family *Methanosaetaceae*, and representatives of *Methanosarcinaceae* able to perform all three methanogenic pathways.

8. Ruminants are mammals that can obtain nutrients from plant foods by fermenting them in a special part of the stomach - the rumen before being digested - with the help of microorganisms. This process produces large amounts of methane. There are about 200 species of ruminants including both domestic and wild animals such as cattle (all domestic and wild cows), goats, sheep, giraffes, deer, gazelles and antelopes. Due to the intensive development of animal husbandry, domestic cows are numerically the main ruminants considered as producers of CH_4.

The rumen is a large fermentation chamber with movable walls. In the rumen, microbial processes occur under anaerobic conditions at a constant temperature (37-39 °C) and a pH of 6.5-7.0. The rumen is inhabited by a variety of bacteria and archaea, as well as protozoa and fungi. It digests up to 70% of the dry matter of the diet *without the participation of digestive enzymes produced by the animal*. The reason is that the breakdown of fiber and other feed substances is carried out by enzymes of microorganisms. Under the action of cellulolytic bacteria, up to 70% of the digestible fiber is broken down in the rumen. Fungi inhabiting the rumen hydrolyze lignin and xylan and, to a lesser extent, cellulose. Protozoa decompose plant debris and hydrolyze the cell walls of fungi and digest food particles. Microbial fermentation of sugars and amino acids released by hydrolysis produces a large amount of VFA - mainly acetic, propionic and butyric acids – which are absorbed into the animal's body as food components.

However, the importance of microorganisms is not limited to the breakdown of feed to form fatty acids. Fatty acids are not a complete diet and grass is deficient in certain amino acids and vitamins. However, as a result of their metabolic activities, the microorganisms reproduce, increasing their biomass, and are used by the host as a source of complete protein, which contains all the essential amino acids and which satisfies the animal's daily needs for it by 20-30%. In addition, microorganisms synthesize various vitamins and growth regulating factors, protect internal organs from the attachment and development of pathogenic microorganisms, and stimulate the immune system of the animal.

Since VFAs, including acetate, are used by the ruminants themselves, the methanogens in the rumen, unlike the situation in most natural ecosystems, use mainly hydrogen and carbon dioxide to synthesize methane. Methanogenesis is thus a side, but at the same time important, process of removing hydrogen and CO_2, dramatically reducing the volume of gaseous products in the rumen: from a total of 5 volumes of H_2 and CO_2, 1 volume of CH_4 is formed. *Methanobrevibacter ruminantium* and *Methanospirillum hungatei* prevail among methanogenic archaea. The generated methane and residual carbon dioxide are then removed into the atmosphere, mainly during eructation (burping). The amount of gas that can eventually form in the rumen of cattle is up to 100 liters per day, depending on the type of feed.

In the first days after the birth of a baby ruminant, the components of the normal rumen microbiota are transferred to it with the mother's saliva and food.

9. Accumulation of greenhouse gases in the atmosphere and climate change is currently one of the most pressing environmental problems. From this example of methane emissions, it is clearly seen how important a systematic approach is to finding solutions. Increased human activity in industry and agriculture leads to increased rates of emission of all greenhouse gases. A feature of methanogenesis is its predominantly microbiological nature. The study of the process of methanogenesis begins at the level of the microbial methanogenic community and individual methane-forming microorganisms, and ends with global biosphere changes.

The methanogenic microbial community functions under anaerobic conditions. Its main feature is close trophic relationships during the decomposition of complex organic substances. As a result of the sequential degradation of organic matter by various microbial groups, methanogens consume simple organic compounds at the end of the trophic chain and form methane as the final product. To make accurate estimations of the fluxes of methane into the atmosphere, it is necessary to know and study its main sources and the intensity of emissions from them. The data on the rates of greenhouse gas emissions in various ecosystems obtained by scientists make it possible to do long-term forecasts regarding changes in the concentration of greenhouse gases in the atmosphere and their impact on the global climate of the Earth.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.** Among the main greenhouse gases, methane is an energy efficient compound and can be used to generate heat and electricity. Creation of effective systems for its capture, purification and further processing in places of its release, such as landfills, wastewater treatment facilities, as well as livestock complexes, rice fields and wetlands can, in addition to economic benefits, significantly reduce its emissions into the atmosphere and lead to a decrease in the greenhouse effect. Presently, in a number of countries, including Europe, methane generated at landfills is already used for energy production.
- **Goal 12. Ensure sustainable consumption and production patterns.** Important and promising directions in the organization of various industries is the prevention of the release of by-products into the atmosphere and the organization of cycles of reuse and disposal. Among these products, special attention should be paid to chemicals that have a harmful effect on the environment, including greenhouse gases.
- **Goal 13. Take urgent action to combat climate change and its impacts.** In connection with the great importance of the problem of global climate change, it is necessary to develop comprehensive measures to solve it, including careful monitoring of all potential sources of greenhouse gas emissions, the organization of continuous measurements of gas flows into the atmosphere, the development of technologies that reduce the release of greenhouse gases of anthropogenic origin, the organization of a system of learning resources for providing the population with a basic knowledge on greenhouse gases and their impact on the Earth's climate, development of an appropriate methodology for measuring greenhouse gas emissions for various ecosystems.
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.** Important points in this regard are the inclusion of coastal and marine ecosystems in the global monitoring of greenhouse gas emissions, as well as updating of estimates of gas emissions and the improvement of technologies for their measurement in aquatic systems.
- **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.** A relevant measure in this case is to improve the policy for the rational use of forest and soil resources as systems that absorb greenhouse gases. It is also necessary to organize scientific expeditions to study various terrestrial ecosystems in relation to the emission of greenhouse gases and, in particular, methane. It is important to develop measures to prevent land degradation and their contribution to the emission of greenhouse gases into the atmosphere.

Potential Implications for Decisions

1. ***Individual***
   - **a.** Should I use using sprays (deodorant, perfume/cologne, cleaning products, etc., which may be propelled by freons that contribute to the greenhouse effect)?
   - b. How much meat should I eat?
   - **c.** Can I reduce the amount of waste I produce (landfills contribute significant amounts of greenhouse gases)?

2. ***Community policies***
    a. Organization of gas emissions purification systems, creation of methane utilization systems.
    b. Incentivisation of environmentally friendly use of agricultural land
        i. crops, rather than meat, dairy products
        ii. when meat, use of animal wastes to produce methane for energy
        iii. low tillage of soils
        iv. low methane production practices for rice paddies
        v. use of biofertilisers, rather than chemical fertilisers
        vi. avoidance of stubble burning practices
        vii. use of biopesticides, rather than chemical pesticides
    c. Creation of green spaces; planting of trees
    d. Regulations limiting the covering of soil/land with impermeable materials, like concrete
    e. Creation/maintenance of wetlands (biodiversity conservation; methane sources)
    f. Education programmes about greenhouse gases and global warming

3. ***National policies***
    a. Policies and regulations to minimize greenhouse gas emissions
    b. Use of economic models that incorporate all costs, especially ecosystem services and environmental damage, rather than externalising environmental costs
    c. Investment in research and development on alternatives to fossil fuels as sources of energy and chemicals
    d. Investment in the bioeconomy
    e. Investment in new technologies to reduce methane emissions in agriculture
    f. Incentivising use of greenhouse gases, in particular methane, for energy needs
    g. Incentivising improved methods of soil cultivation and general agriculture.
    h. Licensing of industries based on their impact on the environment.
    i. Following the international agreement (since 2015 - the Paris Agreement) within the framework of the UN Framework Convention on Climate Change

Pupil Participation

1. ***Class discussions***

a. *Enhancing of systems thinking*. Understanding the phenomenon of the greenhouse effect and its impact on climate change, the different contributions to the greenhouse effect of various gases.

b. *Understanding the role of natural and anthropogenic sources of greenhouse gases in the greenhouse effect*. Carbon dioxide as a greenhouse gas of predominantly anthropogenic origin, methane as a greenhouse gas of predominantly microbial origin.

c. *Contribution to understanding the need to reduce anthropogenic greenhouse gas emissions.* Estimation of carbon dioxide and methane emissions from industrial enterprises and as a result of extensive farming and animal husbandry.

d. *Understanding the mechanisms of methane formation by microorganisms.* Contribution to the study of methane formation in swamps and the symbiotic relationship between ruminants and the methanogenic microbial community, gaining insight into methods for measuring greenhouse gases in various ecosystems

2. ***Pupil stakeholder awareness***

a. Plants, and especially trees, remove CO_2 from the atmosphere. Can I play a part in reducing the community carbon footprint by planting plants or trees?

b. Ruminants are a major source of dietary protein and methane emissions: how can we balance our desire to reduce greenhouse gas emissions and our enjoyment of hamburgers or other meat products?

3. ***Exercises***

a. To grow and develop well, we need plenty of protein. Meat is an excellent source of protein. But there are others. What are they? What are their nutritional advantages and disadvantages? What are their greenhouse gas footprints per meal compared with different types of meat?

b. Assess the economic activities that can be especially significant sources of greenhouse gases and anthropogenic methane, in particular. Consider how they might replace such economic activities with others that would involve production of less methane.

The Evidence Base, Further Reading and Teaching Aids

The greenhouse effect. https://scied.ucar.edu/longcontent/greenhouse-effect
Global Methane Emissions Soaring, But How Much Was Due to Wetlands? https://newscenter.lbl.gov/2020/08/13/global-methane-emissions-soaring-but-how-much-was-due-to-wetlands/
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What is the greenhouse effect? https://www.youtube.com/watch?v=BPJJM_hCFj0
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Ruminant Digestion – Methane. https://www.youtube.com/watch?v=3NG5foxD2HI
The Rumen and Its Microbes. https://www.youtube.com/watch?v=9gr90_OwtSc
Science experiment burning methane swamp gas. https://www.youtube.com/watch?v=XkEV1i_stD4

Glossary

Anaerobic microbial community - various groups of microorganisms living in anoxic conditions and closely related to each other by trophic (substrate, nutritional) interactions.
Cell wall - is a structural layer surrounding some types of cells including cells of algae, fungi and plants. It provides the cell with both structural support and protection, and also acts as a filtering mechanism.
Cellulolytic bacteria - are microorganisms that decompose the polymer cellulose. They secrete the enzyme cellulase, which breaks down (hydrolyzes) cellulose into its monomers (glucose).
Eructation - the release of air or gas from the stomach through the mouth - burping. Eructation is usually caused by a buildup of air in the stomach or the rumen in ruminants.

Freons (trademark) - are several chlorofluorocarbon compounds (CFCs). They are gases or liquids that are used in commerce and industry as propellants in aerosol sprays and refrigerants.
Fungi - are the group of organisms that includes microorganisms such as yeasts and molds, as well as mushrooms. In ruminants they may play a significant role in the assimilation of fibrous feeds by ruminants
Greenhouse effect - the process of the planet's surface warming caused by the presence of gases absorbing and emitting radiant energy in the atmosphere.
Greenhouse gases - gaseous compounds of natural and anthropogenic origin that create a greenhouse effect
Landfills - locations where waste materials are buried underground. It is a low area of land that is built up from solid refuse disposed in layers and covered by soil.
Methanogenic archaea (methanogens) - a group of anaerobic microorganisms that are capable of producing methane from a limited number of chemical sources, and are situated at the end of the trophic chain of the anaerobic microbial community.
Methanotrophic bacteria - a group of microorganisms that utilize methane as their source of carbon and energy
Pathogenic microorganisms - are organisms which are capable of causing diseases in a host. They include fungi, bacteria, viruses and protozoa.
Photosynthesis - is a process used by various organisms (plants, algae, bacteria) to convert light energy into chemical energy that, through cellular respiration, can later be released to fuel the organism's activities. The captured energy is stored in synthesized carbohydrate molecules, such as sugars and starches. Photosynthesis is largely responsible for producing and maintaining the oxygen content of the Earth's atmosphere.
Polystyrene - is a polymer made from the monomer styrene, a liquid hydrocarbon that is commercially manufactured from petroleum and is used in architectural and engineering applications and as packaging material. It can be solid or foamed. Polystyrene foam was formerly made totally with the aid of chlorofluorocarbon blowing agents. Now this technology has been modernized and uses ecologically friendly compounds.
Polyurethane - are a class of polymers that have achieved commercial significance due to their tough mechanical properties. They have many different applications such as manmade skin and leathers for garments, sports clothes, and a variety of accessories, rigid foams for refrigerator and freezer thermal insulation systems, biomaterials for medicine such as heart valves or artificial blood vessels as well as household materials which includes floors and flexible foam padding cushions.
Protozoa - are single celled organisms of different shapes and sizes They are both free living in a wide variety of moist habitats (fresh water, marine environments, soils) and host-dependent (parasitic or symbiotic). Their presence in ruminants results in a higher and more stable ruminal digestion of organic matter.
Pyrolysis - is the process of thermal decomposition of organic materials at elevated temperatures in an inert atmosphere with production of various volatile compounds including methane.
Refrigerant - chemical compound that is used as a working fluid (the heat carrier) in the refrigeration cycle, where it changes from gas to liquid and then back to gas. These changes in state are accompanied by heat loss or gain. Refrigerants are used primarily in refrigerators/freezers, air-conditioning, and fire suppression systems.
Rice fields (paddy fields) - are flooded fields of arable land used for growing semiaquatic crops such as rice. Cultivated land parcels prepared for rice production consist of periodically flooded flat surfaces where anaerobic microorganisms can develop and generate methane.
Rumen - is the largest stomach compartment in ruminants. It is an ideal habitat for the growth of anaerobic microorganisms that digest tough plant fibres (cellulose).

Ruminants - are large hoofed herbivorous mammals that are able to acquire nutrients from plant-based food by fermenting it in a specialized stomach prior to digestion, principally through the action of methanogenic microbial community. Ruminants and products derived from them are a major source of food everywhere in the world.
Wastewater treatment - is the process of cleaning wastewater into water that can be discharged back into the environment. Its main and important part is the biological waste water treatment in which microorganisms effectively remove organic contaminants from heavily organic-laden wastes.
Wetlands - are distinct ecosystems that are flooded by water, either permanently or seasonally. Flooding results in oxygen-free (anoxic) processes prevailing, especially in the soils. They are the most potent natural source of atmospheric methane.
Xylan - is a major structural polysaccharide, a type of hemicellulose in cell walls of plants that represents the third most abundant biopolymer on Earth.