Why Can Cattle Live on Grass, but Humans Cannot?

Introduction

A Biological Puzzle: Matter, Energy, and Digestive Systems
Dr. Ramirez displays an image of a pasture and poses a question to the class:

"Imagine a human and a cow standing in the same field. Both require energy to survive. Both perform cellular respiration to produce adenosine triphosphate (ATP), the primary energy carrier molecule in all living cells. Both depend on organic molecules that ultimately originated from plants. Yet only one of them can survive on grass alone."

She explains that humans can chew and swallow grass, but most of the plant material passes through the digestive system largely unchanged (as it is with most other plant materials that humans ingest). In contrast, cattle can consume grass and other plant products and transform it into usable energy, body tissue, milk, and growth.

Dr. Ramirez emphasizes that this difference is not caused by the grass itself. Grass contains plant cells made of carbohydrates, proteins, lipids, and structural molecules. Instead, the key difference lies in how each organism processes matter and energy through digestion.

From a systems perspective, this biological puzzle connects several scientific processes:

- Photosynthesis, where plants store solar energy in chemical bonds
- Molecular structure, including the differences between starch and cellulose
- Digestive anatomy, such as monogastric versus ruminant systems
- Microbial fermentation in anaerobic environments
- Cellular respiration and ATP production
- Cycling of carbon through biological and atmospheric systems

She highlights that grass contains large amounts of cellulose, a structural carbohydrate composed of glucose units linked by β-1,4 glycosidic bonds. These bonds store chemical energy, but only organisms with the appropriate enzymes and digestive structures can access that energy.

Dr. Ramirez then introduces a key comparison: cattle are ruminants with a specialized, microbe-rich fermentation chamber (the rumen) that allows microbial digestion of cellulose before absorption. Humans are monogastric and lack both a rumen and the enzyme cellulase, meaning much of the chemical energy in cellulose remains biologically inaccessible.

“You have been asked to investigate a systems-level biological puzzle:
How does the unique digestive system of cattle allow them to transform grass into protein-rich biological products, and how does this process connect to matter cycling, energy flow, and biological outputs within Earth’s systems?”

Prompt 1

Dr. Ramirez listens as students suggest that cows get energy from grass. She walks to the window, pulls a blade of grass from outside and holds it up.

“Before we talk about digestion, we need to understand what is actually inside this grass and how its matter and energy got there.”

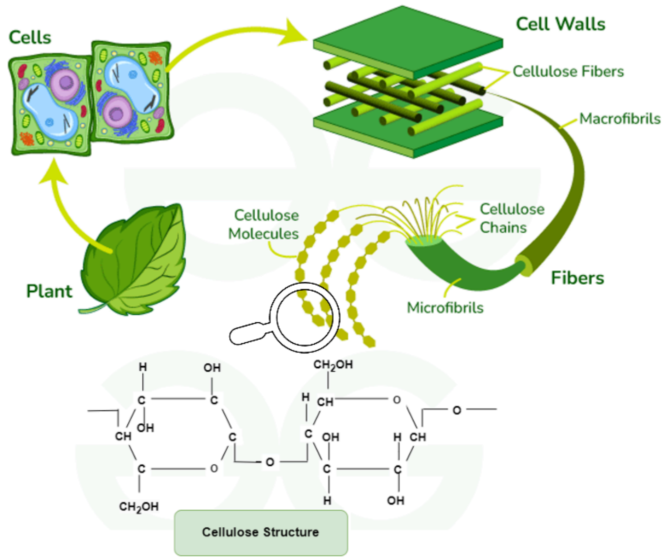
She writes two words on the board:
MATTER and ENERGY

Grass is made of plant cells that contain organic molecules built primarily from carbon, hydrogen and oxygen. The carbon atoms in grass were once part of atmospheric carbon dioxide (CO_2). Through photosynthesis, plants capture light energy from the sun and use it to rearrange carbon dioxide and water into glucose: $6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$

“This process transforms light energy into chemical energy stored in the bonds of glucose molecules. Plants use glucose not only for immediate energy needs, but also as a building block to construct larger carbohydrates that make up plant tissues.”

Two important plant carbohydrates are:

- Starch – used for energy storage
- Cellulose – used for structural support in plant cell walls



The image above shows a plant cell wall, all its individual components, and a zoom in to the structure of cellulose molecules within the microfibrils.
Adapted from: https://www.geeksforgeeks.org/biology/cellulose-in-digestion-herbivores-termites-ruminants/

Cellulose is the primary structural component of grass. It forms rigid cell walls that give plants strength and shape. Chemically, cellulose is made of repeating glucose molecules connected by β-1,4 glycosidic bonds. Although starch and cellulose are both made from glucose, their bond structures differ:

- Starch contains α-1,4 bonds
- Cellulose contains β-1,4 bonds

These different bond orientations change the three-dimensional structure of the molecule and influence which enzymes can break them.

“As a result, much of the energy in grass is stored in the chemical bonds of cellulose within plant cell walls.”

She adds one final note to the board:
Sunlight → Glucose → Cellulose → Plant Biomass

“So now we know:

- The energy in grass originally came from sunlight.
- The carbon in grass came from atmospheric CO_2.
- Much of that energy is locked inside cellulose-rich plant cell walls.

Now we must ask a deeper scientific question:
Can every organism access the chemical energy stored in cellulose? Why or why not?"

1a. Construct a model (diagram, flow model or annotated system model) that shows the pathway of carbon from atmospheric CO_2

- Into glucose during photosynthesis
- Into cellulose molecules
- Into plant tissue (grass biomass)

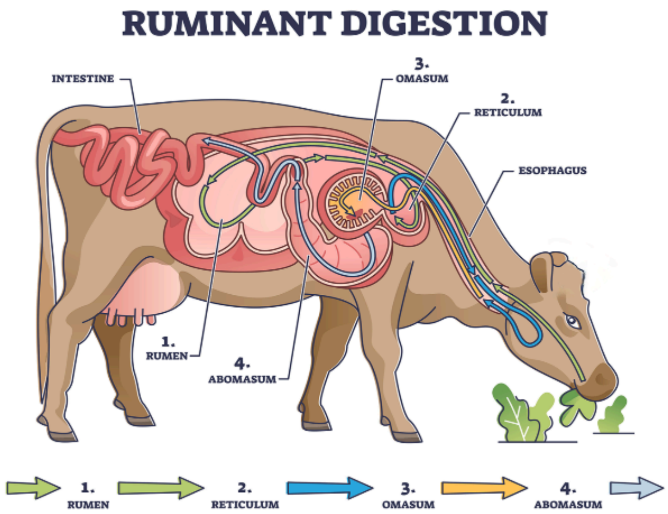
Your model must include:

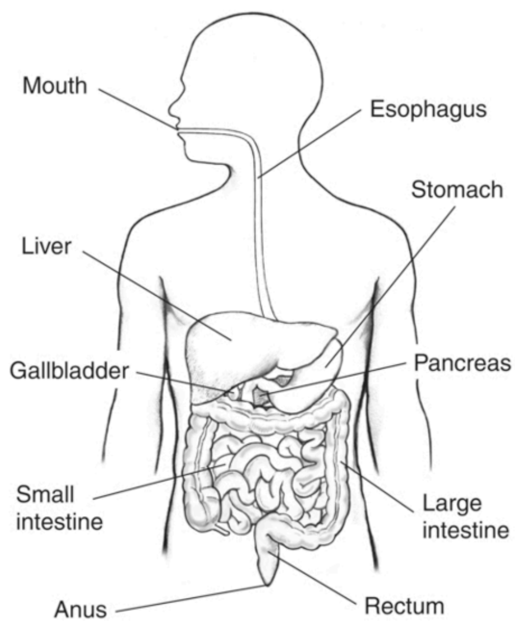
- Where energy enters the system (sunlight)
- How light energy is transformed into chemical energy
- How carbon atoms become part of plant biomass
- Where chemical energy is stored within cellulose-rich plant cell walls

1b. Using evidence from your model, explain why cellulose stores usable chemical energy.

Prompt 2

Dr. Ramirez shares two diagrams, a ruminant and a monogastric digestive system, shown below.





The images above show the internal digestive structures for cattle (left) and humans (right).

“If both organisms eat plants, why does only one thrive on grass?”

All animals rely on digestion to break large food molecules into smaller, absorbable units that can be used in cellular respiration. In many animals, including humans, digestion relies primarily on:

- Stomach acid
- Enzymes produced by the pancreas and small intestine
- Mechanical breakdown through chewing and muscle contractions

These enzymes are highly specific. Humans produce enzymes that break down:

- Starch (α-1,4 bonds)
- Proteins
- Lipids

However, humans do not produce cellulase, the enzyme required to break the β-1,4 glycosidic bonds found in cellulose, the primary component of plant cell walls.

Figure 1. Ruminant Digestion

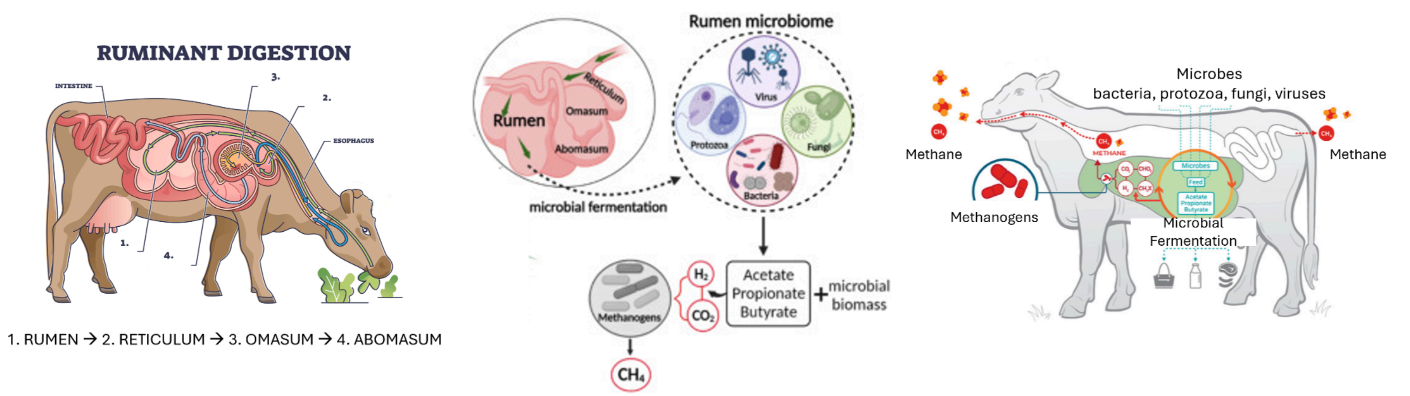


Image Sources:
Edited Adobe Stock # 901451058
https://www.sciencedirect.com/science/article/pii/S0022030225000438
Adapted - https://www.mdpi.com/2076-2615/12/24/3452

Cattle and other ruminants have a specialized four-chambered stomach. The largest chamber, the rumen, functions as a fermentation chamber.

Inside the rumen:

- Billions of bacteria, protozoa, and fungi live in symbiosis within the rumen.

- These microorganisms produce cellulase, the enzyme that breaks cellulose into glucose units or smaller carbohydrates that microbes can ferment.
- Cellulose is broken down under anaerobic (oxygen-free) conditions through a process called fermentation.

During fermentation:
- Complex carbohydrates are chemically transformed into volatile fatty acids (VFAs).
- Carbon dioxide (CO_2) and methane (CH_4) are produced as byproducts.
- Methane is released primarily through eructation (a process similar to human belching).

Unlike humans, cattle absorb significant amounts of fermentation products (VFAs) directly through the rumen wall, before the small intestine. These products of microbial digestion serve as energy sources, allowing cattle to extract energy from cellulose early in the digestive process.

Figure 2. Human Digestion

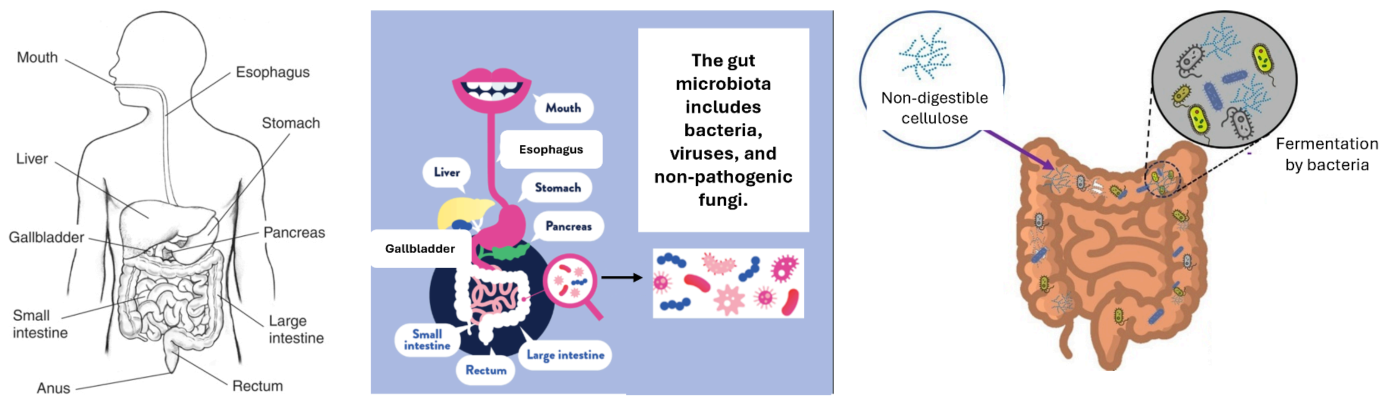


Image Sources :
Edited - https://www.yogurtinnutrition.com/tag/gut-microbiota/
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Humans are monogastric organisms. Digestion begins in the mouth with mechanical breakdown and enzyme activity (amylase) and continues in the stomach and small intestine. Unlike ruminants, humans lack a large fermentation chamber prior to nutrient absorption and do not produce cellulase, the digestive enzyme required to break the β-1,4 glycosidic bonds in cellulose.

Most nutrient absorption in humans occurs in the small intestine before significant microbial fermentation takes place. While some microbes in the large intestine can partially ferment fiber, this occurs after the primary absorption stage, meaning very little chemical energy from cellulose becomes available to human cells. As a result, cellulose functions mainly as dietary fiber rather than a major energy source.

This structural and biochemical limitation explains why humans cannot efficiently access the chemical energy stored in grass, even though that energy is present at the molecular level.

Although humans host gut microbes in the large intestine, this microbial activity is limited compared to the rumen and occurs after most digestion and absorption, contributing minimally to energy extraction from cellulose.

Dr. Ramirez gives students the following comparison table.
"This will help you track how matter enters, is transformed within, and exits the digestive systems of cattle and humans, with a focus on fermentation, biological outputs, and conservation of matter."

Table 1. Comparative Digestion

System Component	**Cattle**	**Humans**
Feeding Strategy	Herbivore	Omnivore
Type of Food Molecules Consumed (Inputs)	Primarily plant biomass, such as grass, that is high in cellulose and complex carbohydrates	Mixed diet including plant and animal products (starches, sugars, proteins, fats);

		cellulose present but not a primary energy source
Presence of Cellulose in Diet	High cellulose intake from grass and forage	Cellulose is present in plant foods, but is not efficiently digested
Oxygen Availability in Main Digestive Environment	Anaerobic (oxygen-free) rumen supports microbial fermentation	Mostly acidic and oxygen-influenced digestion; limited anaerobic fermentation in large intestine
Primary Location of Fermentation	Rumen (before most nutrient absorption)	Large intestine (after most nutrient absorption)
Role of Microorganisms	Dense populations of bacteria, protozoa, fungi and methanogenic archaea that ferment cellulose	Smaller microbial populations that ferment small amounts of fiber in the large intestine
Ability to Break Down Cellulose	High — microbes produce cellulase to break β-1,4 glycosidic bonds in cellulose	Very low — humans lack cellulase and cannot break β-1,4 bonds in cellulose
Absorbable Molecules (Outputs)	Volatile fatty acids (acetate, propionate, butyrate), amino acids and other metabolic intermediates used for energy and growth	Glucose (from starch digestion), amino acids, fatty acids; minimal absorbable products from cellulose
Gases Produced During Digestion	Carbon dioxide (CO_2) and methane (CH_4) are produced during microbial fermentation and respiration	Carbon dioxide (CO_2) and small amounts of gas, such as methane, from limited fermentation
Waste Products	Undigested material, microbial biomass and fermentation residues	Undigested fiber (cellulose) and other waste material
Biological Source of Methane	Methanogenic archaea in the anaerobic rumen use fermentation products (CO_2 and H_2) to produce methane	Very limited methanogenic activity due to the lack of rumen and reduced anaerobic fermentation
Energy Yield from Cellulose	High — cellulose is fermented into VFAs that can be used in cellular respiration	Very low — cellulose passes through largely as dietary fiber

2a. Using the background information, construct a comparative model or table that identifies each of the following for both cattle and humans:

Inputs:

- Type of food molecules consumed

- Presence of cellulose
- Oxygen availability in digestive environments

Outputs:
- Absorbable molecules (e.g., glucose, VFAs, amino acids)
- Gases produced (CO_2, CH_4)
- Waste products (fiber, undigested material)

Your response must:
- Identify where fermentation occurs in cattle vs. humans
- Explain why methanogenesis occurs in ruminants but not significantly in humans
- Describe the biological source of methane
- Connect digestion byproducts to conservation of matter

2b. Create an explanation using your model that:
- Identifies where fermentation occurs in cattle vs. humans
- Explains why methanogenesis occurs in ruminants but not significantly in humans
- Explains why cellulose remains largely undigested in humans
- Describes the biological source of methane

• Connects digestion byproducts to conservation of matter

Prompt 3

"As we just explored, cattle have a really unique digestive system compared to ours. So, cattle don't digest grass alone. They rely on symbiotic microbes to access the matter and energy stored in plant cell walls."

She draws a large systems diagram connecting the sun, plants, microbes, and the cow.

"Let's step back and trace what is actually moving through this biological system."

She writes two headings:
MATTER (carbon atoms) and ENERGY (chemical energy in bonds)

"The carbon atoms in cellulose originally came from atmospheric carbon dioxide that was fixed by plants during photosynthesis. Plants use glucose produced during photosynthesis to build cellulose in their cell walls, storing both carbon and chemical energy in the bonds of this structural carbohydrate."

She adds an arrow:
Atmospheric CO_2 → Glucose → Cellulose in Grass

Dr. Ramirez circles the word cellulose on the board.

"When cattle consume grass, that cellulose does not disappear. Instead, the carbon atoms are rearranged through microbial fermentation in the rumen."

Inside the rumen:

- Microorganisms produce cellulase, which breaks β-1,4 glycosidic bonds in cellulose
- Cellulose is chemically transformed into volatile fatty acids, which the cow uses as a primary energy source.
- Carbon dioxide (CO_2) and small amounts of methane (CH_4) are produced as natural byproducts of this microbial fermentation process.

"These molecules still contain carbon atoms that originated in atmospheric CO_2. Some of these carbon-containing molecules are absorbed and used by the animal, while others are released as gases. Volatile fatty acids are absorbed through the rumen wall and enter the bloodstream, where they are transported to cells throughout the body.

Inside the cells:

- Acetate and butyrate can be converted into acetyl-CoA
- Propionate is converted into glucose in the liver
- These molecules enter cellular respiration pathways in the mitochondria

"During cellular respiration, the chemical energy stored in these bonds is converted into ATP, the usable energy that powers biological processes such as muscle growth, milk production, protein synthesis, and cell maintenance. "

She underlines three key energy transformations:

- Light energy → chemical energy in glucose (photosynthesis)
- Chemical energy in cellulose → chemical energy in VFAs (fermentation)
- Chemical energy in VFAs → ATP (cellular respiration)

“Throughout this entire process, energy is not created. It is transformed. And carbon is not destroyed. It is rearranged and cycled through biological and atmospheric systems.”

She draws one final pathway on the board:

CO_2 (atmosphere) → Grass (glucose → cellulose) → Rumen (microbial fermentation → VFAs + CO_2 + CH_4) → Cells (ATP production) + CO_2 (released)

“So, when we model this system, we are not just drawing digestion. We are tracing how matter and energy move through interconnected biological processes.”

3a. Develop and use a systems model to trace matter and energy from sunlight to ATP in cattle.
Your model must include:

- Photosynthesis (sunlight → glucose)
- Cellulose formation in plant cell walls
- Consumption of plant biomass by cattle
- Microbial fermentation in the rumen and what happens in the bloodstream
- Volatile fatty acid (VFA) absorption
- Cellular respiration in mitochondria
- ATP production in cattle cells

Your model should also clearly illustrate:

- The movement of carbon atoms through each stage
- Where chemical energy is stored and transformed in molecular bonds
- How fermentation products enter metabolic pathways
- The conservation of matter and energy across the biological system

3b. After constructing your systems model, write a scientific explanation that:

- Traces the movement of carbon atoms from atmospheric CO_2 to ATP-producing processes in cattle
- Identifies where major energy transformations occur in the system
- Explains how fermentation products (VFAs) enter cellular respiration pathways
- Describes how matter is conserved as molecules are transformed across biological processes
- Demonstrates how energy is transformed (not created) throughout the system

Prompt 4

Dr. Ramirez writes on the board:
Grass → Energy → Growth → Muscle → Milk

"Cattle don't just extract energy. They transform plant-derived carbon into biological structures, including animal protein, such as meat and dairy products."

She underlines the word carbon.

"Remember, the carbon atoms in grass originally came from atmospheric CO_2 captured during photosynthesis. Those carbon atoms become part of plant biomass, including cellulose and other organic molecules."

When cattle consume grass, microbial fermentation in the rumen transforms plant molecules into volatile fatty acids, which are absorbed into the bloodstream and transported to cells throughout the body. Once inside cells, these carbon-containing molecules enter metabolic pathways where they can be used both to produce energy and to build new biological molecules.

She adds another pathway to the board:
Plant Carbon → VFAs → Metabolic Intermediates → Amino Acids → Proteins

"Proteins are built from amino acids, which contain carbon, hydrogen, oxygen, and nitrogen. The carbon skeletons of amino acids can be derived from plant-based molecules that enter cellular metabolic pathways."

ATP produced during cellular respiration provides the energy required for biosynthesis, including the chemical reactions that link amino acids together to form proteins. These proteins are then used to build and repair tissues, such as muscle, and to support milk production.

She pauses and reminds the class:

"Energy is transformed to power biosynthesis, and matter is conserved as carbon atoms are rearranged from atmospheric CO_2 into plant biomass and ultimately into animal tissue, like the meat and dairy products we consume."

4a. Develop a systems model that traces the transformation of carbon from

atmospheric CO_2 to animal protein in cattle. Your model must trace carbon through:

- Atmospheric CO_2
- Photosynthesis in grass
- Plant biomass (including cellulose)
- Fermentation products (VFAs)
- Metabolic pathways in cattle cells
- Amino acid synthesis
- Muscle and milk production

Your model should clearly show where carbon atoms are rearranged and incorporated into biological structures.

4b. Create an explanation using your model that:

- Describes how ATP provides the energy required for protein synthesis
- Explains how plant-derived carbon becomes incorporated into amino acids and animal

tissue • Connects energy transformation to growth, tissue development and food production • Demonstrates conservation of matter as carbon is rearranged across biological processes

Humans, like all organisms, use cellular respiration to convert food molecules into ATP. Although humans cannot digest cellulose, they can digest proteins, fats, and carbohydrates from foods like meat. During digestion, these molecules are broken down into smaller components that can enter cellular respiration pathways in human cells to produce energy.

4c. Extend your system model to include a human. Add a description to your model to explain: • How energy originally captured by plants becomes part of animal tissue • How humans digest and absorb these molecules • How these molecules are used by cells to produce ATP through cellular respiration

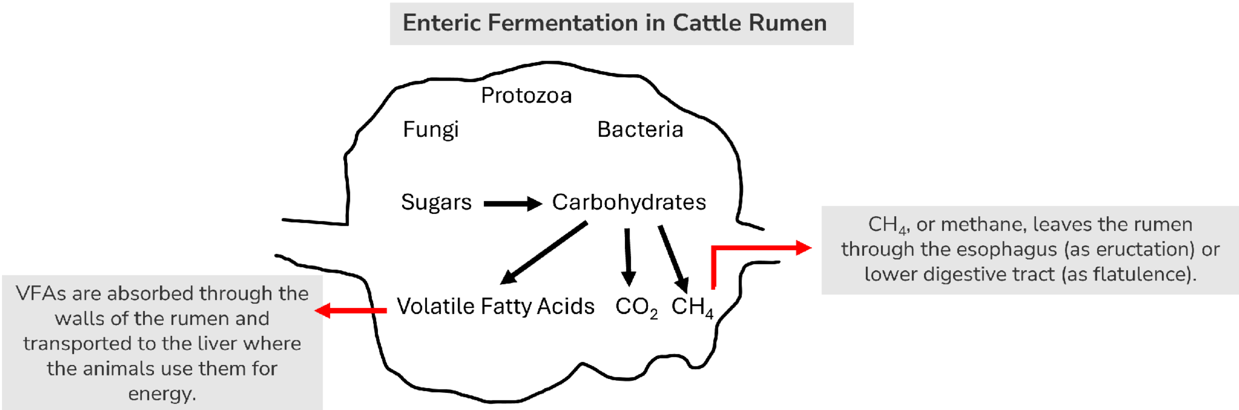
Prompt 5

Dr. Ramirez returns to the systems model drawn on the board and adds a new arrow leaving the cow.

“We have traced how carbon moves from atmospheric CO_2 to plant biomass, through digestion, and into animal tissue, but not all of the carbon remains inside the organism.”

She circles the rumen and writes: Biological Outputs

“During microbial fermentation in the rumen, carbon-containing molecules from plant biomass are continuously transformed. Some carbon atoms are incorporated into volatile fatty acids and animal tissues, while others are released as gaseous byproducts.”



The image above is a diagram of a cow's digestive system showing enteric fermentation in the rumen. Arrows show food entering the cow and methane gas (CH_4) being released as waste and volatile fatty acids (VFAs) being absorbed and transported to the liver for energy.

Adapted from: https://letstalkscience.ca

She adds to the model:
Plant Carbon → Fermentation → CO_2 + CH_4 + Biomass

"Methanogenic microorganisms in the rumen utilize carbon dioxide and hydrogen produced during enteric fermentation to generate methane (CH_4) under anaerobic conditions. This methane contains carbon atoms that originally came from atmospheric CO_2 that was fixed by plants during photosynthesis."

She draws a looping arrow back to the atmosphere.

"These gases are released from the digestive system, primarily through eructation (similar to belching), and enter the atmosphere. Over time, methane is chemically oxidized in the atmosphere and converted back into carbon dioxide, continuing the cycling of carbon through biological and atmospheric systems."

She pauses and underlines a key idea:
"Throughout this entire process, carbon is not created or destroyed. It is conserved and continuously rearranged as it moves between the atmosphere, plants, microorganisms, animals, and back to the atmosphere."

5a. Construct a scientific systems model that connects cattle digestion to the atmospheric cycling of carbon.

Your model must show:

- CO_2 uptake by plants during photosynthesis
- Carbon storage in plant biomass (including cellulose)
- Carbon transformation during microbial fermentation in the rumen
- Carbon release as CO_2 into the atmosphere
- Production of CH_4 as a biological byproduct of fermentation

- How methane exits the cow (biological release pathway)

Your model should also:

- Trace the movement of carbon atoms across biological and atmospheric systems
- Show where carbon is incorporated into biomass and where it is released as gases
- Represent the system as a cycle

5b. Use your model to explain how carbon is conserved as it moves through interconnected biological and atmospheric systems. In your explanation:

- Trace the pathway of carbon from atmospheric CO_2 to plant biomass, animal systems and atmospheric outputs
- Describe how carbon atoms are rearranged during fermentation, respiration and biosynthesis
- Explain how biological outputs (CO_2 and CH_4) return carbon to the atmosphere
- Demonstrate conservation of matter across the entire system

Prompt 6

Dr. Ramirez returns to the systems model on the board, tracing arrows from sunlight to plants, to microbes, cells throughout the body, and finally to biological outputs.

“So far, we have traced how matter and energy move through interconnected biological systems - from atmospheric carbon dioxide to plant biomass, through digestion, metabolism, and into animal tissue.”
She circles two pathways on the model:
Biological Products and Biological Outputs

“During digestion, carbon-containing molecules from plant biomass are continuously transformed. Some carbon atoms are incorporated into volatile fatty acids, amino acids, and proteins that support growth and milk production, while others are released as gaseous byproducts such as carbon dioxide (CO_2) and methane (CH_4) during fermentation and cellular processes."

She adds a looping arrow back to the atmosphere.
"These gases exit the biological system and return carbon to the atmosphere, continuing the cycling of matter between Earth's systems and living organisms."

Then she draws a second pathway:
Grass → Fermentation → VFAs → ATP → Biosynthesis → Muscle & Milk

"At the same time, these digestive and metabolic processes that release biological byproducts also enable cattle to convert plant biomass into protein-rich tissues and food products."

She turns to the class and concludes:
"To fully understand this biological system, we must synthesize how digestion, microbial processes, energy transformation, and biosynthesis work together to:

1. Produce gaseous biological outputs as part of normal metabolic processes, and
2. Convert plant-derived matter and energy into animal growth and protein production."

6a. Explain how the digestive and microbial processes in cattle result in the production of gaseous biological outputs. In your scientific explanation:

- Describe how cellulose is transformed during microbial fermentation in the rumen
- Explain the role of microorganisms, including methanogenic microbes, in anaerobic fermentation
- Identify the major gaseous byproducts of digestion (CO_2 and CH_4) as biological outputs
- Connect digestion and fermentation to the cycling of carbon between biological systems and the atmosphere
- Demonstrate conservation of matter as carbon atoms are rearranged and released as different molecules

6b. Explain how cattle convert grass into protein-rich biological products compared to humans. In your scientific explanation:

- Integrate digestive structure and function (ruminant vs. monogastric systems)
- Describe microbial fermentation and volatile fatty acid (VFA) production
- Trace the flow of energy from cellulose to ATP through cellular respiration
- Explain how ATP supports the biosynthesis of amino acids and proteins
- Describe how plant-derived carbon becomes incorporated into animal tissues such as muscle and milk
- Compare why humans cannot efficiently convert cellulose-rich plant biomass into protein-rich biological structures