FOCUS QUESTIONS
- How and why has animal agriculture impacted global biodiversity over the last few hundred years?
- What are some ways that science can reduce our dependence on traditional animal agriculture?
- How can we use the science of biochemistry to help solve our current biodiversity crisis?
- What is heme, what role does it play in an organism's physiology, and how did heme play a central role in the origin story of Impossible Foods?

OVERVIEW
"I was looking at a bunch of sources, and there was published evidence out there that animal agriculture was a big problem for climate, and there was very little awareness of this as a problem in the world. When I started looking at biodiversity, then I realized, okay, that's probably even a worse problem due to the huge land footprint of animal agriculture."

"It's not that we need to eventually solve this problem. We need to solve it as fast as possible." - Dr. Pat Brown, Professor Emeritus, Stanford University, Founder and CEO, Impossible Foods.

In 2009 Pat Brown took an 18-month sabbatical from his career as a Stanford University Biochemist. Brown had already established himself as a brilliant scientist, having invented the DNA microarray technology and been inducted into the U.S. National Academy of Sciences. Brown used this time away from lab research to search for a way he could use his knowledge of biochemistry to have a lasting and positive impact on the two most pressing environmental challenges of modern time: climate change and biodiversity loss. Brown knew that a leading cause of climate change and biodiversity loss is our over-dependence on land use for agriculture. Brown never returned to the lab and seven years later the Impossible Burger made its debut in U.S. restaurants. ***WILD HOPE: Mission Impossible*** tells the story of how Pat Brown took a wild idea for transforming our food technology with the hope of reducing our animal agricultural footprint and greenhouse gas emissions while restoring wildlife habitat and biodiversity.

KEY CONCEPTS
- Threatened and Endangered Species: The International Union for the Conservation of Nature lists more than 44,000 species threatened with extinction. Habitat loss and destruction and agriculture are the major threats for more than 85% of these species.
- Climate change: As humans pump more greenhouse gasses into the atmosphere the Earth's land areas are seeing more hot days and heat waves, the oceans are warming and rising, storms and droughts are more severe, species are disappearing, and humans are facing more environmental health risks. A major source of greenhouse gasses is animal agriculture. Replacing our attraction to eating agricultural animals for food with alternatives that people will equally seek out and enjoy can move us quickly to a more sustainable carbon future.
- Biodiversity loss: The International Union for the Conservation of Nature lists more than 44,000 species threatened with extinction and animal agriculture is the major threat for more than half of these species. Allowing patches of land that have been used for decades for agricultural production to be returned to a more natural state can help mitigate the threats to biodiversity.
- Conservation biology: The practice of conservation biology recognizes the intrinsic value of the Earth's natural diversity of organisms. Conservation biology works to understand how the natural world operates, how humans affect nature, and how we can use collective scientific and cultural knowledge to conserve Earth's biological diversity.
- Restoration ecology: Centuries of unsustainable human activities have degraded the Earth's terrestrial, freshwater, and marine ecosystems. Restoration ecology is focused on reversing this degradation by restoring natural habitats and processes.

- Technology revolution: At the time Pat Brown began launching his "impossible mission," global animal agriculture was a $1.5 trillion global market, but it was being served by a technology that was too inefficient and too slow to improve enough to reverse its devastating impacts on the environment.
- Genetically modified organisms: A genetically modified organism, or a genetically engineered organism, is an organism whose genes have been changed with biotechnology rather than selective breeding. In ***Mission Impossible*** we learn how yeast have been genetically modified to produce a form of heme called leghemoglobin that is used to give the Impossible Burger its distinctive meat taste.

BACKGROUND

When Pat Brown took a sabbatical from his successful career as a Stanford University biochemist, he was hopeful that he could use his knowledge of biochemistry to help solve a pressing global problem. Brown was already concerned about climate change and he was aware that a major source of excess atmospheric carbon dioxide was animal agriculture. Brown also knew that centuries of animal agriculture has wreaked havoc on many of the Earth's natural terrestrial habitats and the species that depend on them. For example, nearly 23% of the Earth's arable land has been converted from natural habitat to land for raising cattle. At roughly 800 billion kg, the World's cows outweigh the World's humans two-to-one, and in an average year in the United States there are 30 million cows slaughtered for beef.

For decades food companies have developed protein sources, like plant-based burgers, that are intended to function as alternatives to meat and reduce the environmental impact of growing animals for food. However, the availability of these alternatives has not produced a noticeable reduction in global meat consumption, especially in developed countries like the United States. Instead, according to the United Nations Food and Agricultural Organization, the annual per capita consumption of beef, pork, and poultry increased in the United States from 1961 to 2021 from roughly 90 kg (198 lbs) to 125 kg (275 lbs), an increase of almost 40%. Globally this per person meat consumption averages around 40 kg (88 lbs) per year. However, some countries consume less than 4 kg (8.8 lbs) per person per year. Is it possible that a technology revolution in how we produce food could bring developed countries, like the United States, closer to the low meat consumption of many other countries? Is it possible to reduce our global animal agriculture footprint and increase natural habitat and the biodiversity it holds and conserve the Earth's threatened and endangered species? Biochemist Pat Brown was convinced that the answer was "Yes!" So only two years after he began his sabbatical, Brown had founded Impossible Foods with the goal of producing an alternative to meat that frequent meat eaters would seek out and consume with as much enjoyment as they do with animal meat.

But what is it about animal meat, especially beef, that draws so many people to consume it in such high quantities? The production of muscle (meat) and its components in an animal is a biochemical process, so Brown approached the problem as a biochemical scientist would. Brown and his team hypothesized that the key to meat's attractive flavor and color was blood, and more specifically the iron containing heme protein in red blood cells. Heme is super abundant in meat because heme is the key structure in red blood cell hemoglobin and muscle cell myoglobin that binds to oxygen. Indeed, the amount of heme in animals is astounding. For example, there are over one billion heme molecules in a single red blood cell and there are roughly 180 million red blood cells in a kilogram (2.2 lbs) of mammal muscle. Thus, a pound of beef could have as many as 82 billion heme molecules. But heme is also a critical component of heme enzymes which are used in various biological processes including detoxification and oxidation and reduction reactions. Pat Brown understood that he could not solve the problems animal agriculture creates for habitat and biodiversity by simply asking people to change their diets and stop eating meat. Instead, he had to change the way we make meat by eliminating the animals themselves. The "mission impossible" for Brown and his team of biochemists became how to find a plant-based source of heme and a way to mass produce it so they could add it to the new meat product they were developing.

Brown and his team simply followed the scientific process. First, they dug into the published literature to find plant based sources of heme. They discovered that the root nodules on soy plants that fix atmospheric nitrogen are packed with a heme-containing compound called leghemoglobin. The team first thought they could easily harvest the root nodules of soy plants that were left over from soybean production and extract the heme. They spent a year-and-a-half trying to develop an efficient harvesting method and failed. This failure led Brown and his team back to biochemistry where they were able to isolate the gene for leghemoglobin, transfer it to the genomes of yeast, and engineer the yeast as factories for heme.

With the founding of Impossible Foods and the successful development of its flagship product, the Impossible Burger, Pat Brown has turned a large part of his focus to another important question: What can we do with the land we have freed up from animal meat production? The Impossible Foundation is a non-profit organization Brown is working with to help landowners reimagine their land through reforestation with the potential to connect to future carbon markets where companies and governments pay landowners to conserve. The new Carbon Ranch that Brown has helped develop in Arkansas is an example of how the restoration ecology of reforestation can not only help reverse climate change through the natural carbon capture process of photosynthesis, but also restore biodiversity back to the land.

The ***Mission Impossible*** film tells this fascinating and hopeful story of discovery and innovation and reminds the viewers that one of the most important roles scientists play in society is to challenge the status quo and improve not only the human condition, but also solve the problems created by humans ourselves.

BIODIVERSITY THREATS

The major threats to the Earth's biodiversity can be grouped into seven categories that spell the easily recalled acronym H.I.P.P.O.: **H**abitat destruction and fragmentation, **I**ntroduced species, **P**ollution, **P**opulation growth, and **O**verharvesting. Many species are threatened by a combination of these factors, but habitat loss is the greatest threat to biodiversity. In Mission Impossible we learn that centuries of habitat destruction through the conversion of land to agriculture has significantly contributed to the loss of biodiversity. However, this effect can be mitigated in large part with innovations to our food technology systems that replace animal meat with alternatives that will satisfy even the most carnivorous among us.

DISCUSSION QUESTIONS

- [Before showing the film] Have students list and describe all of the animal meat alternatives they can think of that are on the market today. Have students also discuss whether or not they have tried these products and what they think of them.
- [Before showing the film] Have students research and discuss how synthetic human insulin is produced and how many people benefit from this technology. Ask them to discuss if they have ever eaten food that was from a genetically modified organism. Ask the students to discuss what they think about genetic modification in the production of food.
- [Before showing the film] Introduce students to the How Science Works interactive tool at HHMI BioInteractive. Print copies of the detailed How Science Works map for each student. Ask students to use their maps to diagram Pat Brown and his team's process of science as it is described in the film. After watching the film, students share their maps with each other and then create a consensus model with the class. Finally, have students compare the class consensus to the textbook model of the "scientific method."
- Have students discuss their reactions to what they learned from watching the film and learning about the story of the invention of the Impossible Burger.

- Have students describe the process of engineering yeast to produce leghemoglobin for the purpose of producing a product that looks and tastes like meat. Ask students to discuss how they feel about the fact that the yeast are a genetically modified organism. Ask students to compare their feelings about using genetically modified yeast to produce a food alternative to help solve the biodiversity crisis with their feelings about using a genetically modified bacterium to produce insulin to help solve the diabetes crisis. How similar or different are the two processes and their goals?

Curriculum Connections
NGSS
HS-LS2 Ecosystems: Interactions, Energy, and Dynamics
- LS2.A: Interdependent Relationships in Ecosystems
- LS2.B: Cycles of Matter and Energy Transfer in Ecosystems
- LS2.C: Ecosystem Dynamics, Functioning, and Resilience
- LS2.D: Social Interactions and Group Behavior
- LS4.D: Biodiversity and Humans
- PS3.D: Energy in Chemical Processes

ETS1.B: Developing Possible Solutions

AP Biology (2021)
Enduring Understandings
- Energetics (ENE)
    - ENE-1: The highly complex organization of living systems requires constant input of energy and the exchange of macromolecules.
    - ENE-4: Communities and ecosystems change on the basis of interactions among populations and disruptions to the environment.
- Information Storage and Transmission (IST)
    - IST-2: Differences in the expression of genes account for some of the phenotypic differences between organisms.
- Systems Interactions (SYI)
    - SYI-3: Naturally occurring diversity among and between components within biological systems affects interactions with the environment.

IB Biology (First Exam May 2025)
A. Unity and Diversity: Common ancestry has given living organisms many shared features while evolution has resulted in the rich biodiversity of life on Earth.
- A3.1 Diversity of organisms
- A4.2 Conservation of biodiversity

B. Form and Function: Adaptations are forms that correspond to function. These adaptations persist from generation to generation because they increase the chances of survival.
- B1.1 Carbohydrates and lipids
- B1.2 Proteins
- B4.2 Ecological niches

C. Interaction and Interdependence: Systems are based on interactions, interdependence and integration of components. Systems result in emergence of new properties at each level of biological organization.
- C1.1 Enzymes and metabolism
- C1.3 Photosynthesis
- C4.2 Transfers of energy and matter

D. Continuity and Change: Living things have mechanisms for maintaining equilibrium and for bringing about transformation. Environmental change is a driver of evolution by natural selection.

- D1.3 Mutation and gene editing
- D2.2 Gene expression
- D4.3 Climate change

REFERENCES

Eisen, M. B., & Brown, P. O. (2022). Rapid global phaseout of animal agriculture has the potential to stabilize greenhouse gas levels for 30 years and offset 68 percent of CO_2 emissions this century. *PLoS Climate*, *1*(2), e0000010.

Food and Agriculture Organization of the United Nations (2023) – with major processing by Our World in Data. “Per capita consumption of beef – FAO” [dataset]. Food and Agriculture Organization of the United Nations, “Food Balances: Food Balances (2013, old methodology and population)”; Food and Agriculture Organization of the United Nations, “Food Balances: Food Balances (2010-)” [original data].

Friend, T. (2019). Can a burger help solve climate change? *The New Yorker*. https://www. newyorker. com/magazine/2019/09/30/can-aburger-help-solve-climate-change. Accessed 20 October 2024.

Hatton, I. A., Galbraith, E. D., Merleau, N. S., Miettinen, T. P., Smith, B. M., & Shander, J. A. (2023). The human cell count and size distribution. *Proceedings of the National Academy of Sciences*, 120(39), e2303077120.

Pimentel, D., & Pimentel, M. (2003). Sustainability of meat-based and plant-based diets and the environment. *The American Journal of Clinical Nutrition*, 78(3), 660S-663S.

USDA. (2023). *Cattle*. USDA, National Agricultural Statistics Service. https://downloads.usda.library.cornell.edu/usda-esmis/files/h702q636h/ms35vn48m/fj237f291/catl0123.pdf. Accessed 29 September 2024.

CREDIT

Written by Paul K. Strode, Ph.D., Fairview High School, Boulder, Colorado