RethinkX

*Disruption, Implications, and Choices*

# Rethinking Food and Agriculture 2020-2030

## The Second Domestication of Plants and Animals, the Disruption of the Cow, and the Collapse of Industrial Livestock Farming

A RethinkX Sector Disruption Report
September 2019
Catherine Tubb & Tony Seba

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# The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

Rethinking Food and Agriculture is the second in a series of reports that analyzes the impacts of disruption, sector by sector, across the economy. We aim to produce analyses that reflect the reality of fast-paced, technology-adoption S-curves. Mainstream analysts produce linear, mechanistic, and siloed forecasts that ignore systems complexity and thus consistently underplay the speed and extent of technological disruptions – for example solar PV, electric vehicles, and mobile phone adoption. By relying on these mainstream forecasts, policymakers, investors, and businesses risk locking in inadequate or misguided policies and investments, resource misallocation and negative feedbacks that lead to massive wealth, resource, and job destruction as well as increased social instability and vulnerability.

We take a systems approach to analyze the complex interplay between individuals, businesses, investors, and policymakers in driving disruption and the impact of this disruption as it ripples across the rest of society. Our methodology focuses primarily on market forces that are triggered by technology convergence, business model innovation, product innovation, and exponential improvements in both cost and capabilities.

RethinkX's follow-on analyses will consider the cascading and interdependent effects of technology disruption within and across sectors. Our aim is to inspire a global conversation about the threats and opportunities of technology-driven disruption and to focus attention on choices that can help lead to a more equitable, healthy, resilient, and stable society.

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**With Thanks**

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Our thanks in no way implies agreement with all (or any) of our assumptions and findings.
Any mistakes are our own.

# Preface

This study is built on the Seba Technology Disruption Framework set out in our report Rethinking Transportation 2020-2030 (published May 2017). An update to the framework will be published in Q4 2019.

This analysis focuses on the new technologies driving the transformation of the food and agriculture sectors and the inevitable implications for the cattle industry in the U.S. The cost curves we have produced are based on limited data given the early stage of the application of these technologies in food markets. These cost curves underpin the adoption and implications analysis presented in this paper. They should be seen as a 'beta' analysis or a 'first pass' and we will update them as more evidence emerges. We welcome feedback that will help in developing this analysis.

The pace of development of new technologies and their adoption and the processes that drive the concurrent collapse of industrial farming depend on many interacting factors, including policy and social responses to the disruption, responses that are inherently uncertain and difficult to model. Clearly, the further out in time the model runs, the less certainty there is, but we believe our proven framework, methodology, and findings capture the direction of travel and the complex processes involved. The exact timing of the disruption may shift by a handful of years depending on the choices made across society.

Our core model runs to 2030. By then, our central scenario shows that the disruption will be irreversible but incomplete – so our analysis considers a period out to 2035 to provide a more complete picture. We focus on cattle but have extrapolated our findings to cover all livestock and the impact on arable crop farming, global agriculture, and beyond. Given the magnitude of the disruption, society should be prepared for the dramatic changes to an industry that has not seen this scale of disruption in thousands of years.

We will continue to track the disruption of food and agriculture as well as disruptions in key sectors such as energy and transportation. All of these disruptions are interconnected and dynamic and will affect every aspect of our world – cities, organizations, markets, economics, finance, geopolitics, health, environment, and more.

# Disclaimer

# Executive Summary

We are on the cusp of the deepest, fastest, most consequential disruption in food and agricultural production since the first domestication of plants and animals ten thousand years ago.

This is primarily a protein disruption driven by economics. The cost of proteins will be five times cheaper by 2030 and 10 times cheaper by 2035 than existing animal proteins, before ultimately approaching the cost of sugar. They will also be superior in every key attribute – more nutritious, healthier, better tasting, and more convenient, with almost unimaginable variety. This means that, by 2030, modern food products will be higher quality and cost less than half as much to produce as the animal-derived products they replace.

The impact of this disruption on industrial animal farming will be profound. By 2030, the number of cows in the U.S. will have fallen by 50% and the cattle farming industry will be all but bankrupt. All other livestock industries will suffer a similar fate, while the knock-on effects for crop farmers and businesses throughout the value chain will be severe.

This is the result of rapid advances in precision biology that have allowed us to make huge strides in precision fermentation, a process that allows us to program micro-organisms to produce almost any complex organic molecule. These advances are now being combined with an entirely new model of production we call Food-as-Software, in which individual molecules engineered by scientists are uploaded to databases – molecular cookbooks that food engineers anywhere in the world can use to design products in the same way that software developers design apps. This model ensures constant iteration so that products improve rapidly, with each version superior and cheaper than the last. It also ensures a production system that is completely decentralized and much more stable and resilient than industrial animal agriculture, with fermentation farms located in or close to towns and cities.

This rapid improvement is in stark contrast to the industrial livestock production model, which has all but reached its limits in terms of scale, reach, and efficiency. As the most inefficient and economically vulnerable part of this system, cow products will be the first to feel the full force of modern food's disruptive power. Modern alternatives will be up to 100 times more land efficient, 10-25 times more feedstock efficient, 20 times more time efficient, and 10 times more water efficient.[1,2] They will also produce an order of magnitude less waste.

Modern foods have already started disrupting the ground meat market, but once cost parity is reached, we believe in 2021-23, adoption will tip and accelerate exponentially. The disruption will play out in a number of ways and does not rely solely on the direct, one-for-one substitution of end products. In some markets, only a small percentage of the ingredients need to be replaced for an entire product to be disrupted. The whole of the cow milk industry, for example, will start to collapse once modern food technologies have replaced the proteins in a bottle of milk – just 3.3% of its content. The industry, which is already balancing on a knife edge, will thus be all but bankrupt by 2030.

This is not, therefore, one disruption but many in parallel, with each overlapping, reinforcing, and accelerating one another. Product after product that we extract from the cow will be replaced by superior, cheaper, modern alternatives, triggering a death spiral of increasing prices, decreasing demand, and reversing economies of scale for the industrial cattle farming industry, which will collapse long before we see modern technologies produce the perfect, cellular steak.

# Summary of Key Findings

» By 2030, demand for cow products will have fallen by 70%. Before we reach this point, the U.S. cattle industry will be effectively bankrupt. By 2035, demand for cow products will have shrunk by 80% to 90%. Other livestock markets such as chicken, pig, and fish will follow a similar trajectory. There will be enormous destruction of value for those involved in rearing animals and processing them, and for all the industries that support and supply the sector (fertilizers, machinery, veterinary services, and more). We estimate this will total more than $100bn. At the same time, there will be huge opportunities for the producers of modern foods and materials.

» Production volumes of the U.S. beef and dairy industries and their suppliers will decline by more than 50% by 2030, and by nearly 90% by 2035. In our central case, by 2030 the market by volume for ground beef will have shrunk by 70%, the steak market by 30%, and the dairy market by almost 90%. The market by volume for other cow products such as leather and collagen is likely to have declined by more than 90%. Crop farming volumes, such as soy, corn, and alfalfa, will fall by more than 50%.

» The current industrialized, animal-agriculture system will be replaced with a Food-as-Software model, where foods are engineered by scientists at a molecular level and uploaded to databases that can be accessed by food designers anywhere in the world. This will result in a far more distributed, localized food-production system that is more stable and resilient than the one it replaces. The new production system will be shielded from volume and price volatility due to the vagaries of seasonality, weather, drought, disease and other natural, economic, and political factors. Geography will no longer offer any competitive advantage. We will move from a centralized system dependent on scarce resources to a distributed system based on abundant resources.

» By 2035, about 60% of the land currently being used for livestock and feed production will be freed for other uses. This represents one-quarter of the continental U.S. – almost as much land as was acquired during the Louisiana Purchase of 1803. The opportunity to reimagine the American landscape by repurposing this land is wholly unprecedented.

*Source: Impossible Foods*

» Modern foods will be cheaper and superior to animal-derived foods. The cost of modern food products will be half that of animal products and they will be superior in every functional attribute – more nutritious, tastier, and more convenient with much greater variety. Nutritional benefits could have a profound impact on health, both in a reduction in foodborne illness and in conditions such as heart disease, obesity, cancer, and diabetes that are estimated to cost the U.S. $1.7 trillion every year.

» Wider economic benefits will accrue from the reduction in the cost of food in the form of increased disposable incomes and from the wealth, jobs, and taxes that come from leading the way in modern food technologies.

» Environmental benefits will be profound, with net greenhouse gas emissions from the sector falling by 45% by 2030. Other issues such as international deforestation, species extinction, water scarcity, and aquatic pollution from animal waste, hormones, and antibiotics will be ameliorated as well. By 2035, lands previously used to produce animal foods in the U.S. could become a major carbon sink.

# Key Impacts of the Food and Agriculture Disruption

### Economic:

- The cost of modern foods and other precision fermentation products will be at least 50% and as much as 80% lower than the animal products they replace, which will translate into substantially lower prices and increased disposable incomes.
- At current prices, revenues of the U.S. beef and dairy industry and their suppliers, which together exceed $400bn today, will decline by at least 50% by 2030, and by nearly 90% by 2035. All other livestock and commercial fisheries will follow a similar trajectory.
- The volume of crops needed to feed cattle in the U.S. will fall by 50%, from 155 million tons in 2018 to 80 million tons in 2030. This means that, at current prices, feed production revenues for cattle will fall by more than 50%, from $60bn in 2018 to less than $30bn in 2030.
- Farmland values will collapse by 40%-80%. The outcome for individual regions and farms depends on the land's alternative uses, amenity value, and policy choices that are made.
- Major producers of animal products are at risk of a serious economic shock. Countries that produce large quantities of conventional animal products and inputs to animal farming like Brazil, where more than 21% of GDP comes from agriculture – 7% of which is from livestock alone – are particularly vulnerable.
- The average U.S. family will save more than $1,200 a year in food costs. This will keep an additional $100bn a year in Americans' pockets by 2030.
- By 2030, at least half of the demand for oil from the U.S. agriculture industry – currently running at about 150 million barrels of oil equivalent a year – will disappear as all parts of the supply chain related to growing and transporting cattle are disrupted.

### Environmental:

- By 2035, 60% of the land currently used for livestock and feed production will be freed for other uses. This 485 million acres equates to 13 times the size of Iowa, an area almost the size of the Louisiana Purchase.
- If all this freed land were dedicated to reforestation and efforts were made to utilize tree species and planting techniques intended to maximize carbon sequestration, all current sources of U.S. greenhouse gas emissions could be fully offset by 2035.
- U.S. greenhouse gas emissions from cattle will drop by 60% by 2030, on course to nearly 80% by 2035. Even when the modern food production that replaces animal agriculture is included, net emissions from the sector as a whole will decline by 45% by 2030, on course to 65% by 2035.
- Water consumption in cattle production and associated feed cropland irrigation will fall by 50% by 2030, on course to 75% by 2035. Even when the modern food production that replaces animal agriculture is included, net water consumption in the sector as a whole will decline by 35% by 2030, on course to 60% by 2035.

**Social:**

- Higher quality, more nutritious food will become cheaper and more accessible for everyone. In the developing world in particular, access to cheap protein will have a hugely positive impact on hunger, nutrition, and general health.
- Half of the 1.2 million jobs in U.S. beef and dairy production and their associated industries will be lost by 2030, climbing towards 90% by 2035.
- The emerging U.S. precision fermentation industry will create at least 700,000 jobs by 2030 and up to one million jobs by 2035.

**Geopolitical:**

- Trade relations will shift because decentralized food production will be far less constrained by geographic and climatic conditions than traditional livestock farming and agriculture.
- Major exporters of animal products, like the U.S., Brazil, and the European Union, will lose geopolitical leverage over countries that are currently dependent upon imports of these products. Countries importing animal products can more easily produce these products domestically at a lower cost using modern production methods.
- Large endowments of arable land and other natural resources are not required to lead the disruption, so the opportunity exists for any country to capture value associated with a global industry worth trillions of dollars that ultimately emerges over the course of this disruption.

# Choices

The disruption of food and agriculture is inevitable – modern products will be cheaper and superior in every conceivable way – but policymakers, investors, businesses, and civil society as a whole have the power to slow down or speed up their adoption. The aim of this report is to start a conversation and focus decision-makers' attention on the scale, speed, and impact of the modern food disruption. The choices they make in the near term will have a lasting impact – those regarding IP rights and approval processes for modern food products, for example, will be critical.

Many decisions will be driven by economic advantages as well as by social and environmental considerations. But other decisions may be influenced by incumbent industries seeking to delay or derail the disruption. They may also be influenced by mainstream analysis, although decisions made based on such analysis tend to make economies and societies poorer by locking them into assets, technologies, and skill sets that are uncompetitive, expensive, and obsolete. To unlock the full potential of this and every other technological disruption, we need to embrace a different approach, one that better reflects the complex, dynamic, and rapidly-changing world we live in.

Decision-makers must also recognize there are no geographical barriers to the food and agriculture disruption, so if the U.S. resists or fails to support the modern food industry, other countries such as China will capture the health, wealth, and jobs that accrue to those leading the way. Policymakers must, therefore, start planning for the modern food disruption now in order to capture the extraordinary economic, social, and environmental benefits it has to offer.

# The New Language of Food

## Cell-based Meat:

Meat that is comprised of animal cells grown outside an animal in a bioreactor. These products are genetically identical to conventional animal products. Cell-based meat is also referred to by others as clean meat, lab-grown meat, cultured meat, or in-vitro meat.

## Chemical Synthesis:

The construction of chemical compounds through a series of chemical reactions or physical manipulations to get from precursors (petrochemical or natural) to organic molecules. Synthesis is used to discover compounds with new physical or biological properties, to produce compounds that do not form naturally, or to make products in large quantities. Products created through chemical synthesis are typically referred to as synthetic or man-made and are alternatives to natural products.

## Computational Biology:

The application of computers and computer science to the understanding and modeling of the structures and processes of life. Computational biology uses methods from a wide range of mathematical and computational fields (for example complexity theory, algorithmics, machine learning, and robotics) to represent and simulate biological systems (for example molecules, cells, tissues, and organs), and interpret experimental data (for example concentrations, sequences, and images), often on a very large scale.

## Enzyme:

A substance that acts as a catalyst, regulating the rate at which chemical reactions proceed without being altered itself.

## Fermentation Tank:

A stainless steel, cylindrical vessel that facilitates various types of biochemical reactions by providing agitation, aeration, sterility, and regulation of factors like temperature, pH, pressure, and nutrient feeding in a closed-system environment. We include bioreactors in this definition. Precision Fermentation uses fermentation tanks while cell-based meat uses bioreactors.

## Food-as-Software:

The new model of food production and consumption that adopts certain principles of modern computing. Like software, food products are continually improved through iteration as technology improves in both cost and capability and as food component databases grow. Food is designed using massive databases of molecules and tweaked for variations such as taste and texture based on consumer preferences or nutritional requirements. Integration with information technology and the internet means that improvements in production methods and/or ingredients can be downloaded and incorporated almost instantaneously, allowing production to be fully distributed and decentralized.

## Form factor:

The size, shape, and functionality of a food, or other, product. The term “form factor” comes from the computer industry – it is the computer or electronic hardware’s overall design and functionality, usually highlighted by a prominent feature such as a QWERTY keyboard.

## Fortification:

Enhancing a product by including elements, such as proteins, that deliver desirable properties like improved nutrition.

## Genetic Engineering:

The direct manipulation, modification, or recombination of DNA in order to modify an organism’s (or population of organisms’) characteristics.

## High-throughput Screening:

An experimentation process relevant to the fields of chemistry and biology, in which hundreds of thousands of samples are subjected to simultaneous testing under given conditions. Enabled by technological advancement in robotics, sensors, and automation, high-throughput screening can quickly, reliably, and easily generate large datasets that can be used to answer complex biological questions.

## Industrial Agriculture:

The industrialized production of livestock, poultry, fish, and crops brought about by the industrial revolution that prioritizes large-scale production, maximum yields, and quick turnover. Industrial agriculture is characterized by confined animal farming operations, chemical pesticides and fertilizers, very large monocrop farming operations, centralized production, and vast distribution networks.

## Macro-organism:

An organism that can be seen with the naked eye.

### Metabolic Engineering:
The targeted and purposeful alteration of metabolic pathways found in an organism to generate useful products at high productivity.

### Micro-organism (microbe):
An organism that can only be seen with a microscope. Many different types of organisms can be classified as microbes, including bacteria, archaea, fungi, protists, viruses, plants, or animals.

### Modern Food:
Food produced by the modern food industry using the new technologies we discuss in this report, be it precision fermentation, cell-based meat, Food-as-Software (which many plant-based foods utilize), or a combination of all.

### Mycoprotein:
A single-celled fungal protein product grown by fermentation.

### Plant-based Meat:
Meat that is made entirely from plant ingredients but is produced in such a way that it resembles traditional, animal-derived meat products such as burgers, steaks, hot dogs, or jerky. Historically, soy has been the most popular choice as the main ingredient in plant-based meat, but recently companies have been successful using other ingredients like wheat, yellow pea, and coconut. These new ingredients have become more prominent due to advances in technology that have enabled superior functionality, including more meat-like flavor profiles, textures, and appearances.

### Precision Agriculture:
Agricultural activity characterized by a strong focus on high-resolution data collection thorough analysis and specific manipulations. Examples include site-specific fertilizer or pesticide application for crop farming, and timed, detailed control of animal care and feeding in livestock. This is distinct from precision biology and precision fermentation as it represents incremental improvement in efficiency of industrial agriculture.

### Precision Biology:
The coming together of modern information technologies like artificial intelligence (AI), machine learning, and the cloud, with modern biotechnologies like genetic engineering, synthetic biology, metabolic engineering, systems biology, bioinformatics, and computational biology.

### Precision Fermentation:
Fermentation plus precision biology. A process that allows us to program micro-organisms to produce almost any complex organic molecule.

### Precision-fermentation Enabled:
Any product or production technique that is improved, or made possible by, advances in precision fermentation costs or capabilities.

### Precision-fermentation Enhanced:
Any product with ingredients made by precision fermentation. These products do not contain animal-derived meat.

### Synthetic Biology:
A discipline in which the main objective is to create fully operational existing or novel biological systems from smaller constituent parts, including DNA, proteins, and other organic molecules, by applying engineering principles to biology.

### Systems Biology:
A holistic approach to deciphering the complexity of biological systems by studying the interactions and behavior of the components of biological entities (for example molecules, cells, organs, and organisms) with the understanding that the whole of a living organism is more than the sum of its parts. The field integrates biology, computer science, engineering, bioinformatics, and physics.

## Part One

# The Second Domestication of Plants and Animals

Ten thousand years ago, the first domestication of plants and animals marked a pivotal point in human history. For the very first time, humans began breeding plants and animals to eat and put to work. These were wild macro-organisms, ranging from cows and sheep to wheat and barley. Humans no longer hunted and gathered their food, but began controlling its production, selecting the best traits and conditions for growing these organisms and thereby, albeit unintentionally, altering their natural evolution.

> **This is the second domestication of plants and animals. The first domestication allowed us to master macro-organisms. The second will allow us to master micro-organisms**

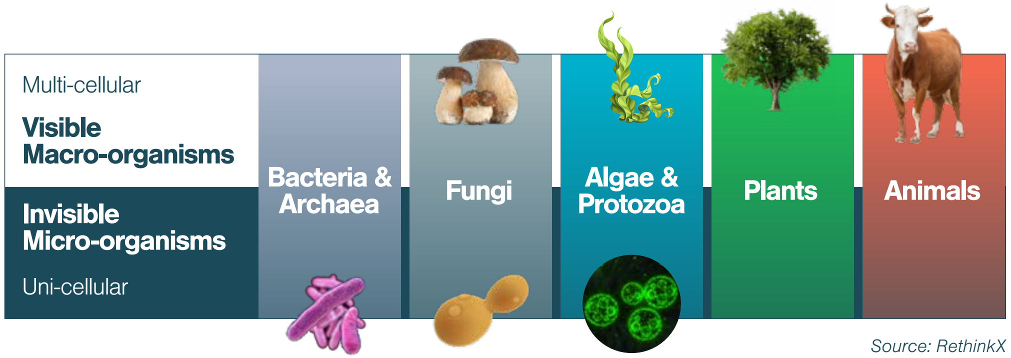
An often-overlooked component of this first domestication is the vital role micro-organisms played. Micro-organisms exist naturally within macro-organisms, breaking down nutrient inputs to build useful outputs. For example, micro-organisms in the digestive tract of a cow help produce the protein and amino acids it needs to live and grow. Not only, then, were humans unintentionally manipulating the evolution of macro-organisms, but micro-organisms as well.

One thousand or so years later, humans were manipulating micro-organisms in a more direct way through early experiments in fermentation. Within controlled environments such as ceramic pots and wooden barrels, humans slowly discovered how to make many staple foods such as bread and cheese, how to preserve fruits and vegetables, and how to produce alcoholic drinks. Humans were now able, in the most rudimentary way, to control the production of food. For thousands of years, the model of food production remained largely unchanged, based on the lessons learned during the first domestication.

Today, we stand on the cusp of the next great revolution in food production. New technologies allow us to manipulate micro-organisms to a far greater degree than our ancestors could possibly have imagined. We can now unplug micro-organisms entirely from macro-organisms and harness them directly as superior and more efficient units of nutrient production.

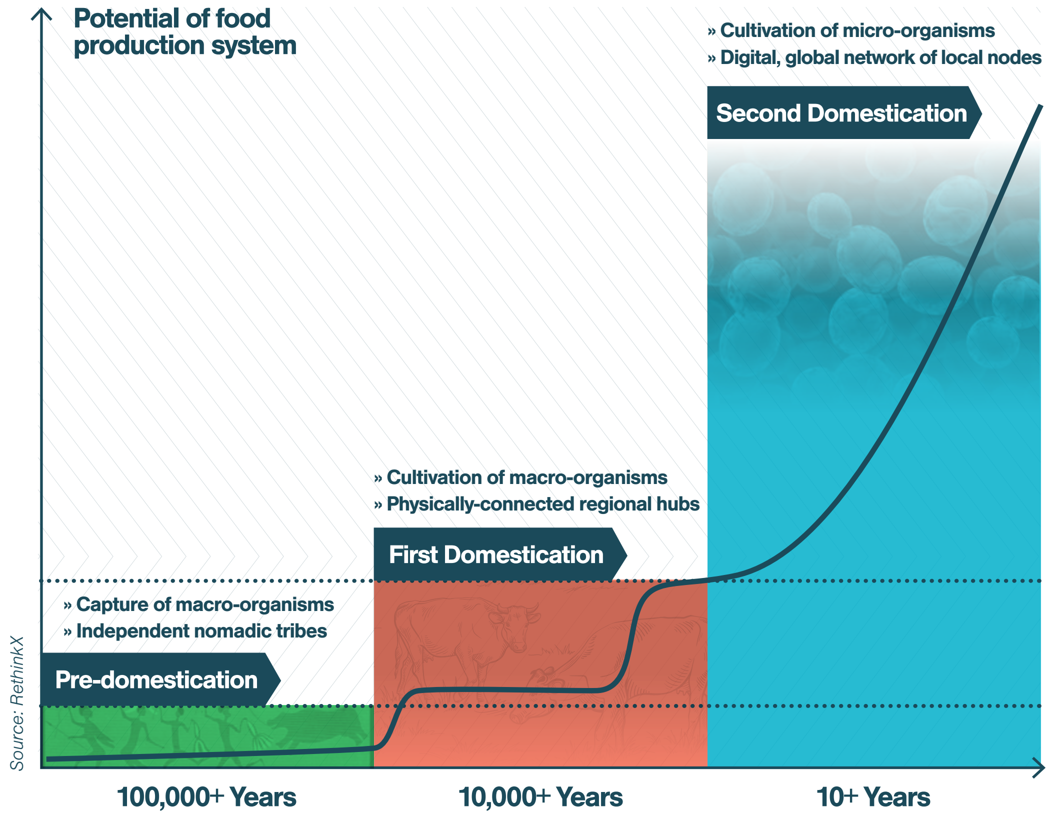
This is the second domestication of plants and animals. The first domestication allowed us to master macro-organisms. The second will allow us to master micro-organisms.

## Figure 1. Domestication of Macro vs. Micro-organisms




Source: RethinkX

## Figure 2. Millennia to Domesticate Macro-organisms, Decades to Domesticate Micro-organisms




Source: RethinkX

## A New System of Production

In the biological sense, food is simply packages of nutrients, such as proteins, fats, carbohydrates, vitamins, and minerals. Of these, proteins – the large molecules that are needed by all cells to function properly – are the most important. They are, quite literally, the building blocks of life.

Macro-organisms produce these packages, but to access the individual nutrients within them requires further processing, which adds additional cost (and diminishes nutritional quality). Single molecules within these packages are, therefore, the hardest and most expensive to extract.[3]

However, micro-organisms produce these individual nutrients directly. Domestication of micro-organisms, therefore, allows us simply to bypass the macro-organisms we currently grow to produce food and access the individual nutrients directly. By doing this, we can build up food from these nutrients to the exact specifications we need, rather than breaking down macro-organisms to access them. We can replace an extravagantly inefficient system that requires enormous quantities of inputs and produces huge amounts of waste with one that is precise, targeted, and tractable.

More than that, by moving production to the molecular level, the number of nutrients we can produce is no longer constrained by the plant or animal kingdoms. While nature provides us with millions of unique proteins, for example, we consume just a fraction of these because they are too difficult or too expensive to extract from macro-organisms. In the new system of production, not only do these proteins become instantly accessible, but millions more that do not even exist today. Free to design molecules to any specification we desire, the only constraint will be the confines of the human imagination. Each ingredient will serve a specific purpose, allowing us to create foods with the exact attributes we desire in terms of nutritional profile, structure, taste, texture, and functional qualities. Virtually limitless inputs will, therefore, spawn virtually limitless outputs (see Box 2).

So bountiful and inexpensive will these proteins be that they will disrupt not just the food and agriculture industries but healthcare, cosmetics, and materials. They will underpin a new production system that represents a profound shift in how we conceptualize, design, and manufacture products across all these sectors. We will be able to design and customize individual molecules to build up products to precise specifications instead of breaking them down from animals, plants, or petroleum.

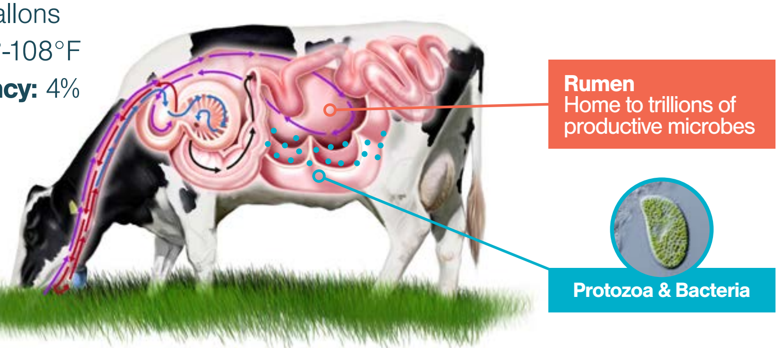
We will, in short, move from a system of scarcity to one of abundance. From a system of extraction to one of creation.

## Figure 3. Precision Fermentation: Protein Production Unplugged

### Cow Protein Production

**Cow Rumen** – the production of protein is the work of many microbes inhabiting the rumen of the cow.

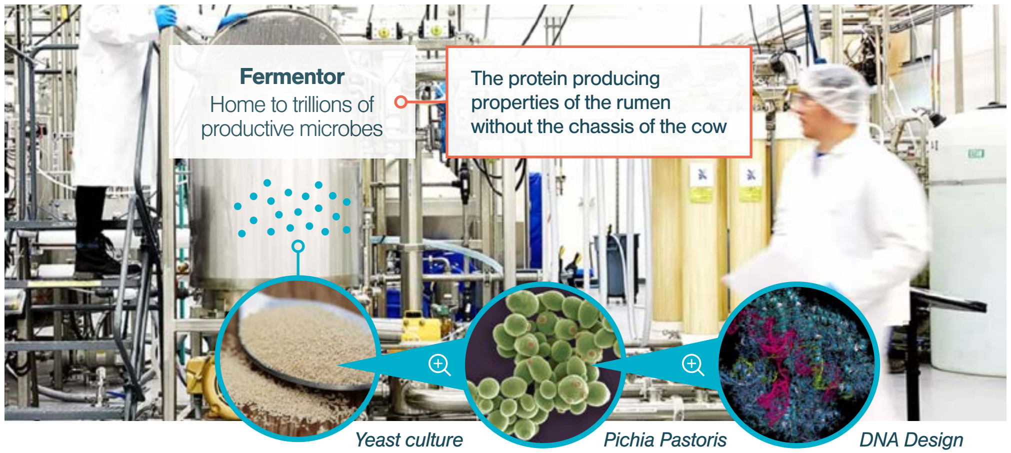
**Capacity:** 40-50 gallons
**Temperature:** 100°-108°F
**Feedstock Efficiency:** 4%




### Precision Fermentation Protein Production

The production of protein is also the work of microbes, designed to manufacture desired proteins in tightly-controlled environments.

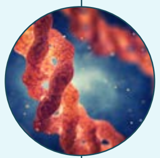
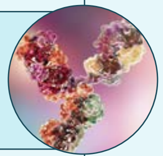
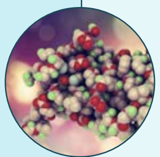
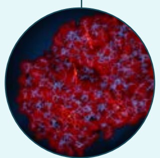
**Capacity:** 50-10,000 gallons
**Temperature:** Optimized
**Feedstock Efficiency:** 40%-80%




*Source: RethinkX, Impossible Foods*

# Box 1: Proteins Make Life Happen

The central dogma of molecular biology describes the two-step process by which the information in genes flows from DNA into proteins. DNA is the information carrier of life. Proteins are the biomolecules that execute an immense number of functions to make life happen. The ability to manipulate proteins confers the ability to manipulate life itself. These are some examples of protein functions:

| Type | Function Description | Examples |
|---|---|---|
| Structural | Provide structure and support for the cell and the body and allow the body to move. | **Keratin** is the major structural fibrous protein to form hair, nails, feathers, and horns. Keratin is a key component of human skin and plays a role in healing wounds. **Collagen** is a protein that connects and supports muscles, bones, tendons, ligaments, blood vessels, organs, and cartilage, and holds skin together.  |
| Antibodies | Help protect the body against foreign particles such as viruses and bacteria. | **Immunoglobulin G (IgG)** is a type of antibody that circulates in the blood and recognizes foreign particles that might be harmful.  |
| Enzymes | Assist with the formation of new molecules by reading the genetic information in DNA. They speed up reactions and carry out almost all of the thousands of chemical reactions that take place in cells. | **Amylase** is an enzyme made by our saliva glands to break down starches into sugars. **Lactase** is a digestive enzyme that helps break down lactose, the sugar in milk.  |
| Messenger Proteins | Transmit signals to coordinate biological processes between cells, tissues, and organs. | **Insulin** is a hormone that is responsible for allowing glucose in the blood to enter cells, providing them with the energy to function. **Growth hormones** regulate cell growth.  |
| Transport Proteins | Bind and carry atoms and small molecules within cells and throughout the body. | **Hemoglobin** is a protein found in red blood cells that carries oxygen from the lungs to every cell in the body. **Ferritin** is involved in iron storage.  |

*Source: RethinkX*

# Box 2: To Infinity and Beyond

The number of possible proteins is effectively infinite. To explain why, we need to understand the role of amino acids (aa).

Proteins are long chains of aa. These linear sequences are held together by different peptide bonds and fold into three-dimensional structures, which give proteins their biological and chemical functionality. Each gene in cellular DNA contains the code for a unique protein structure. There are about 500 aa in nature but only 20 appear in the genetic code.[4] The number of aa in proteins range from about 100 for short ribosomal proteins to 33,423 for titin, which gives human muscles their elasticity. The median length of a eukaryote protein is about 400 aa (the eukaryota domain includes most living organisms, including plants, fungi, and animals).[5]

We have 20 aa choices for each of the 400 positions along the eukaryote protein linear chain. So, the total number of possible unique proteins of length 400 is 20 raised to the power 400 (20^400). Type 20^400 in Google's scientific calculator and the answer is infinity (other calculators simply give an error message).


*Source: Google*

The same is true for prokaryota (bacteria and archea) proteins. Prokaryota protein length is about 300 aa, so the total number of possible unique proteins of length 300 is 20 raised to the power 300 (20^300). Again, the answer is 'infinity'.

Lower the number to 225 aa and we finally get a number – about 10^292. That is 10^212 larger than the number of atoms in the known universe (10^80).

# Box 3: Making the Impossible, Possible

**Human proteins for human consumption:** There are a number of human analogues already – human insulin, collagen, milk proteins, and antibodies. The reason is simple – human proteins are better-suited for human use. For example, just as human collagen works better than bovine, porcine, or jellyfish collagen in cosmetics, human milk proteins would be superior than cow milk proteins in baby formula.

Source: Kosmebox Website

*In March 2019, Geltor announced HumaColl21™, the first human collagen created for cosmetics, calling it "the molecular root of youthful, resilient human skin – selected for its maximum biocompatibility with human skin cells." Geltor CEO, Alex Lorestani, stated: "There are so many naturally-occurring proteins with incredible functions outside of the current animal ecosystem. Our goal is to spearhead the use of bioactive proteins like collagen across new categories." Currently, HumaColl21™ is being used as the hero ingredient in AHC's "Ageless Real Eye Cream for Face", a Korean anti-aging face cream*

**Proteins that are too expensive to extract:**
Many molecules are simply too scarce in nature to find or farm economically. We are already producing plant natural products (PNPs) like natural vanilla, orange flavoring (valencene), sweeteners (non-bitter stevia, thaumatin), vitamins, and cannabinoids directly from micro-organisms more cheaply than from macro-organisms. Soon we will be producing many more. Australian scientists, for example, recently identified and replicated a protein in platypus milk that has unique antibacterial properties.[6] In the modern food production system, the file containing that platypus protein could be uploaded (as data), together with instructions for processing it (software), and made available to anyone, anywhere in the world.


Source: Cargill Website

*Cargill – a major U.S. producer of food, agricultural, financial, and industrial products – applies precision fermentation to make EverSweet™ stevia sweetener. The company describes the secret to "calorie-free joy" as lying in "the age-old technique of fermentation – with a modern twist – using a specially crafted baker's yeast". In other words, a microbe modified to replicate one of the REB M and D molecules in stevia responsible for its sweetness*

**Proteins from extinct plants and animals:** The same process could be used by engineers to replicate proteins from extinct plants and animals. Developing leather or meat from mammoths, giant moas, or Atlantic gray whales will, therefore, be possible. In fact, steaks and leathers of any size, shape, or thickness derived from any organism will soon be achievable.

Source: DARPA

*One example of a new protein being built on-demand, in this case for the Defense Advanced Research Projects Agency, is a form of synthetic polymer for creating medicines resilient to extreme environments*

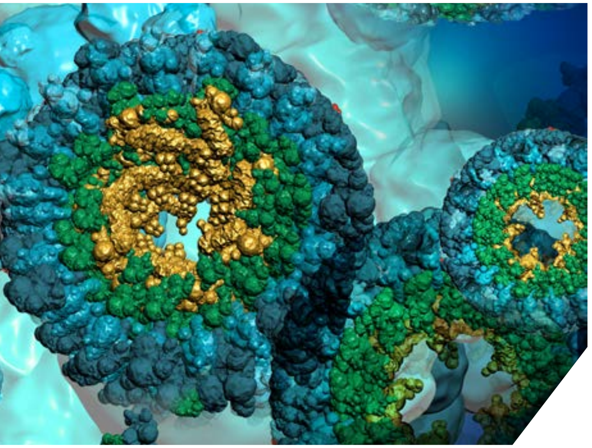
**Proteins that do not exist:** We will be able to design proteins that do not and never have existed before. A group at MIT, for example, has already developed a discovery platform that has generated millions of proteins that are not found in nature.[7]

# 1.1 Technological Convergence Driving Disruption

The driving force behind these new possibilities is precision biology. This encompasses the information and biotechnologies necessary to design and program cells and organisms, including genetic engineering, synthetic biology, systems biology, metabolic engineering, and computational biology.[8]

In essence, synthetic biology has undergone a conceptual shift by becoming an engineering discipline. Just like software developers, synthetic biologists can engineer biology and improve quality, scalability, nutrition, taste, structure, and cost.

New information technologies like machine learning with deep neural networks are allowing scientists to analyze complex biological processes with far greater speed and accuracy than ever before. For example, we now have the technology to annotate a database of 100 million proteins in less than two days using a single computer.[9] Meanwhile, technologies like CRISPR have given scientists new tools to manipulate genetic matter to design specific organisms that can be programed to produce molecules with the precise attributes required.[10]



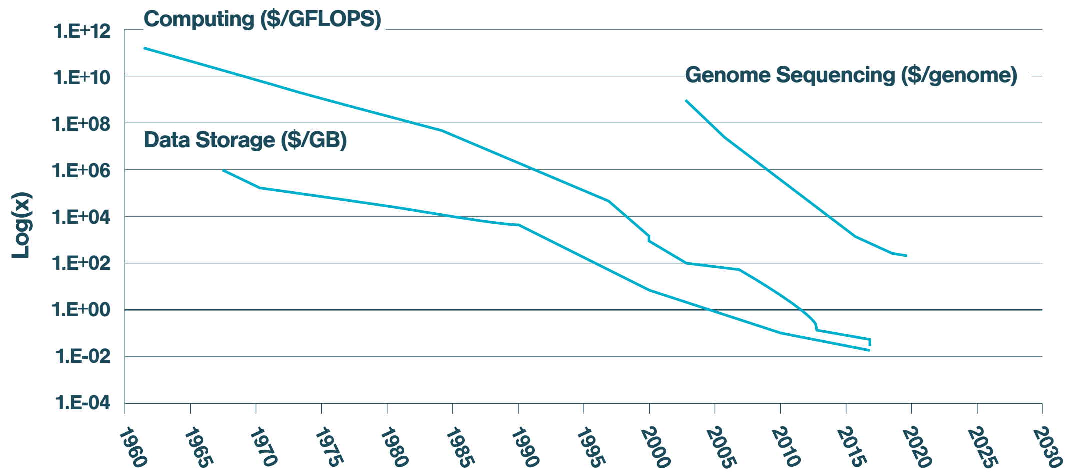
With the aid of artificial intelligence and robotics, this means we can now formulate millions of potential versions of new food products and ingredients and simultaneously analyze and test them through high-throughput screening to ensure the best combination of nutrition, taste, flavor, aroma, and mouthfeel. We have now reached the point where scientists can design and synthesize almost any known or unknown molecule, while rapidly falling costs mean we can do so far more cheaply than ever before.

For example, the cost of fully sequencing the first human genome was $1bn in 2000 and took 13 years.[11] Today, it takes just a few days and costs about $1,000 – with a $100 genome within reach (see Figure 4).[12] The cost of computing was $50m per teraflop in 2000. Today, a GPU for machine learning costs less than $60 per teraflop.[13]

> **"Unlike the cow, we get better at making meat every single day"**
>
> *Pat Brown – CEO Impossible Foods*

When these advances in precision biology are combined with the Food-as-Software production model, where the databases of millions of individual molecules can be updated and shared by scientists in real time with production facilities across the world, food engineers are able to design products in the same way that software developers develop apps for smartphones. Continual iteration means modern food products will improve rapidly, both in functional attributes and in cost – just as version 1.0 hits the market, companies will be working on version 2.0 already, then 3.0, and so on, with every version superior and cheaper than the last. This rapid improvement is in stark contrast to the industrial livestock production model, which has all but reached its limits in terms of scale, reach, and efficiency.

## Figure 4. Costs of Key Underlying Technologies Falling Exponentially




*Source: RethinkX, Bioeconomy Capital (R. Carlson); National Human Genome Research Institute; Federal Reserve Bank of Minneapolis Community Development Project; Computerworld – John C. McCallum*

# 1.2 Precision Fermentation

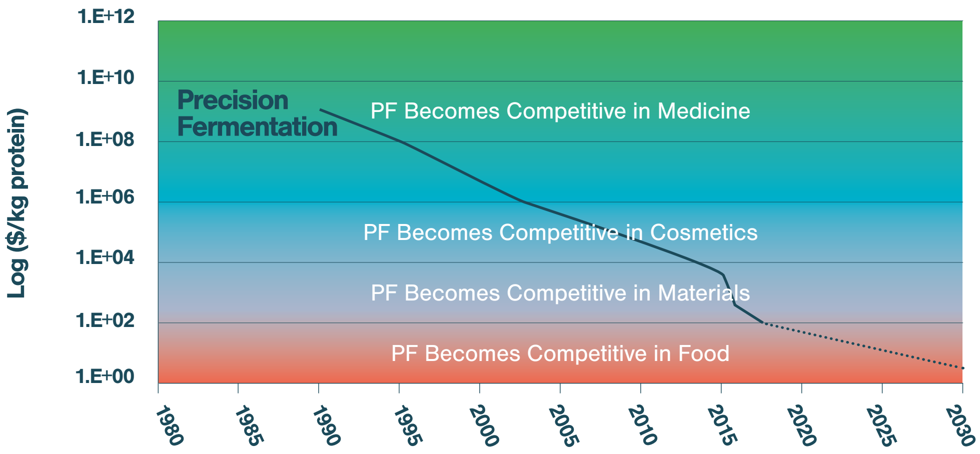
One key process enabled by the convergence of these technologies and their rapidly falling costs is precision fermentation (PF). This is the combination of precision biology with the age-old process of fermentation.[14]

**PF is the process that allows us to program micro-organisms to produce almost any complex organic molecule.[15]** These include the production of proteins (including enzymes and hormones), fats (including oils), and vitamins to precise specifications, abundantly, and ultimately at marginal costs approaching the cost of sugar. These molecules are vital ingredients across a wide range of industries as they bring structure, function, and nutrition to consumer products.[16]

PF is a proven technology that has been used commercially since the 1980s – scientists have been using genetic engineering to modify micro-organisms for producing human insulin[17] (see Box 4) and growth hormone,[18] enzymes such as rennet (chymosin),[19] and various other biologics.[20] A number of vitamins and supplements are produced almost exclusively using PF.[21] More recently, the process is being used to make collagen. Today, these products generate revenues of more than $100bn worldwide every year.[22]

The cost of PF is being driven ever lower by a steep decline in the cost of precision biology. As a result, the cost of producing a single molecule by PF has fallen from $1m/kg in 2000 to about $100/kg today. We expect the cost to fall below $10/kg by 2025.

## Figure 5. PF Disrupting More Industries as Costs Fall




*Source: RethinkX*

This means PF is now on the cusp of outcompeting animal agriculture as a form of food production, not just in cost, but in capabilities, speed, and volume. The end result will be an improvement in the efficiency of current industrial food production by an order of magnitude.

## Box 4: Insulin – the First PF Breakthrough

Insulin is an instructive example of how PF has created a superior product that led to a rapid disruption of an existing product. Historically, insulin used to treat diabetes in humans came from the pancreases of cows and pigs, with more than 50,000 animals needed to produce one kilogram. The insulin extracted then needed expensive processing to reach the level of purity required. In addition, animal-derived insulin was far from perfect – it could lead to severe allergic reactions and was inconsistent in quality. There were also widespread fears in the 1970s about limited and uncertain supply, with forecasts indicating 56 million animals a year would be needed to meet growing U.S. demand.[23]

In 1978, Genentech produced the first genetically modified yeast that was capable of producing human insulin – Humulin. This was approved by the FDA in 1982 and adoption was rapid. Humulin was more consistent in quality, better tolerated, and managed sugar levels more effectively, despite initially being more expensive to produce.[24] By 2000, animal insulin made up less than 1% of the market.[25]


*Source: Humulin*

# Box 5: A Brief History of Fermentation

### Accidental Fermentation:

Fermentation is a chemical process that occurs naturally in micro-organisms as they break down and change organic molecules. Over time, humans recognized its benefits and began to harness fermentation to help make food more digestible as well as to improve its taste, texture, flavor, and aroma. Most importantly, fermentation meant food could be preserved and stored for much longer periods of time (hence why sailors would often drink beer rather than water[26]). Food and drinks like beer, wine, bread, cheese, koji, and miso are all products of this natural process, one that was refined by ancient peoples around the world. While none of these groups had any awareness of micro-organisms or understanding of the intricacies of the fermentation process, fermented products became an important part of people's diets and lifestyles.

**Fermentation was so central to the culture of Ancient Egypt that the hieroglyph for food combines the symbols for fermented favorites beer and bread**

### Industrial Fermentation:

With the advent of microscopes in the 19th century, scientists like Louis Pasteur began to study, control, and manipulate micro-organisms, which in turn led to an understanding of the process of fermentation. This greater understanding, together with huge advances at the turn of the 20th century in the ability to scale up production in a controlled manner, meant we were able to exploit fermentation to make large quantities of a limited number of products, including not just food products but also organic acids, solvents, and industrial enzymes.

### Precision Fermentation:

The advent of precision biology means we can now design and program micro-organisms to produce any products we want.

# Box 6: PF Underpinning New Technologies

Source: Impossible Foods

*PF-produced food ingredients: PF heme in the Impossible Burger*

PF is the key to unlocking the potential for plant-based products and for other new technologies such as cell-based meat.

Turning plants into consumer food products involves specialized ingredients, and PF will allow micro-organisms to produce an infinite number of these ingredients to enhance and improve plant-based products.[27]

PF is also likely to underpin a number of new production technologies, such as producing growth factors for the production of cell-based meat.[28]

To produce cell-based meat, animal cells (muscle, fat, and connective tissue) are harvested and grown in a growth medium in a laboratory and assembled in such a way that they replicate conventional meat products. Ground meats are far easier to replicate than steaks, as they have less structural complexity. The growth medium represents the major cost, but PF has the potential to produce the key growth proteins required, abundantly and at very low cost. Work has been continuing on cell-based meat independently from PF, and while scale-up and product structure remain challenges, huge progress has been made (see Part 2).

Source: Aleph Farms

*PF-enabled food ingredients: PF growth cultures enabling production of cellular meat*

# 1.3 Lower Production and Supply Chain Costs

## Production Costs

To illustrate just how disruptive modern foods will be, we use the example of the cow, which is one of the most inefficient ways to manufacture protein and, therefore, an industry ripe for disruption.

The cattle industry is very resource intensive, with enormous quantities of feed crops, land, water, and time dedicated to the production of animal-based products. Currently, farmers essentially grow an entire cow before breaking it down into specific products, such as steak, leather, or collagen, and the process is nearing its limits in terms of resource efficiency, with little potential to improve costs of production. For example, cow-feed efficiencies have made little to no improvements over the last 30 years.[29] But with PF, a process that will continue to fall dramatically in cost, these products can be produced using the precise number of individual molecules needed.

Modern foods will be about 10 times more efficient than a cow at converting feed into end products because a cow needs energy via feed to maintain and build its body over time. Less feed consumed means less land required to grow it, which means less water is used and less waste is produced. The savings are dramatic – more than 10-25 times less feedstock, 10 times less water, five times less energy and 100 times less land.

PF can also decrease production time from the two to three years currently required to grow a cow to a matter of weeks. These order-of-magnitude improvements in input and time efficiencies will translate into order-of-magnitude lower product costs.

We forecast, therefore, that cost parity with most animal-derived protein molecules will be reached by 2023-25 and, by 2030, the cost of protein production using PF will be five times less than that of animal agriculture. More structurally complex products like steak, which require multiple molecule types and complex structures, will be more expensive to produce and take longer to reach parity. Once protein production falls below $10/kg by 2023-25, the livestock farming industry will begin to collapse and disruption of all forms of meat production becomes inevitable.

During the 2030s, we anticipate the total costs of modern foods will approach one tenth the cost of cow products, while the marginal cost of production will approach the cost of sugar plus energy and water. The carbohydrate-based inputs needed to power modern foods can potentially come from any biomatter (leaves, crops, seaweed, or algae).

## Supply Chain Costs

Modern foods will also bring about an entirely different food production system that will move from the field to the fermentation tank. Eliminating the current supply and value chains associated with cattle production and replacing them with a far more efficient, localized production system that all but eliminates waste and reduces significantly the need for transport will cut distribution costs and price volatility, which will cut product costs further still.

Existing cattle supply chains that are heavily dependent on expansive infrastructure, from large-scale crop farms and slaughterhouses to packing facilities and distributors, will become largely redundant as the line between producers, wholesalers, and retailers blurs. Just like ice shifted from being extracted from northern lakes to being produced in local refrigerators in the late 19th century, food production will shift from large, remote, agricultural areas to smaller, easily accessible, urban areas.

# 1.4 Improvements in Attributes

Modern foods will not only produce food that is cheaper than animal-derived products, but superior in every conceivable way – in quality, taste, structure, nutrition, and impact on the environment and society. In fact, these improvements will ensure that adoption of new products begins before cost parity is reached, just as it has in some markets today.

**Taste:** Attributes related to taste and mouthfeel, such as sweetness, sourness, melt, bite, and texture will represent an improvement on animal-derived foods. Properties related to the structure of foods and their utility will also improve, including emulsification, ability to foam, or to make baked goods rise.

**Convenience:** Modern foods will lead to a system of production that is more distributed, where food can be created and delivered locally far faster and more conveniently than is currently the case.

**Variety:** Modern food technologies will allow the production of foods with an infinite range of properties, including those related to tolerability, allergies, and personalization, meaning consumers will ultimately be able to order food specifically designed to meet their individual needs.

**Nutrition:** Modern food products will be more healthy and nutritionally complete than their animal-derived equivalents. For example, a PF-enabled burger can contain not only less fat and salt than a burger made from a cow, but more vitamins and minerals than a portion of fresh vegetables. Modern proteins should also be more bioavailable than animal proteins.

**Predictability:** A more decentralized and resilient production model, closer to the consumer, means food production will no longer be at the mercy of geography, or of extreme price, quality, and volume fluctuations due to climate, seasons, disease, epidemics, geopolitical restrictions, or exchange-rate volatility. PF foods will also have a longer shelf life and be less vulnerable to contamination risk.

These attributes will affect decisions made by stakeholders across society, and therefore impact the speed of adoption (see Part 2). The importance of each one of these criteria will vary depending on the stakeholder – consumer, business, investor, or policymaker. But to all stakeholders, products made from PF will be demonstrably better on every parameter than food products made by conventional animal agriculture – to consumers who buy food, to businesses who supply it, to investors who help fund its production, and to policymakers who influence the regulatory, fiscal, and policy frameworks that determine the competitiveness of the different production systems. When we also consider the increasing cost savings over conventionally-farmed foods, our analysis indicates that the disruption of industrial food production will be dramatic, both in speed and scope. **Indeed, the conventional industrial food production system has as much chance of competing with modern foods as cuneiform clay tablets have of competing with modern computer tablets or smartphones.**

## Part Two

# Disruption and Adoption

# 2.1 Unbundling the Cow

The second domestication of plants and animals is a continuation of the historic unbundling of the cow by superior and more efficient technologies.

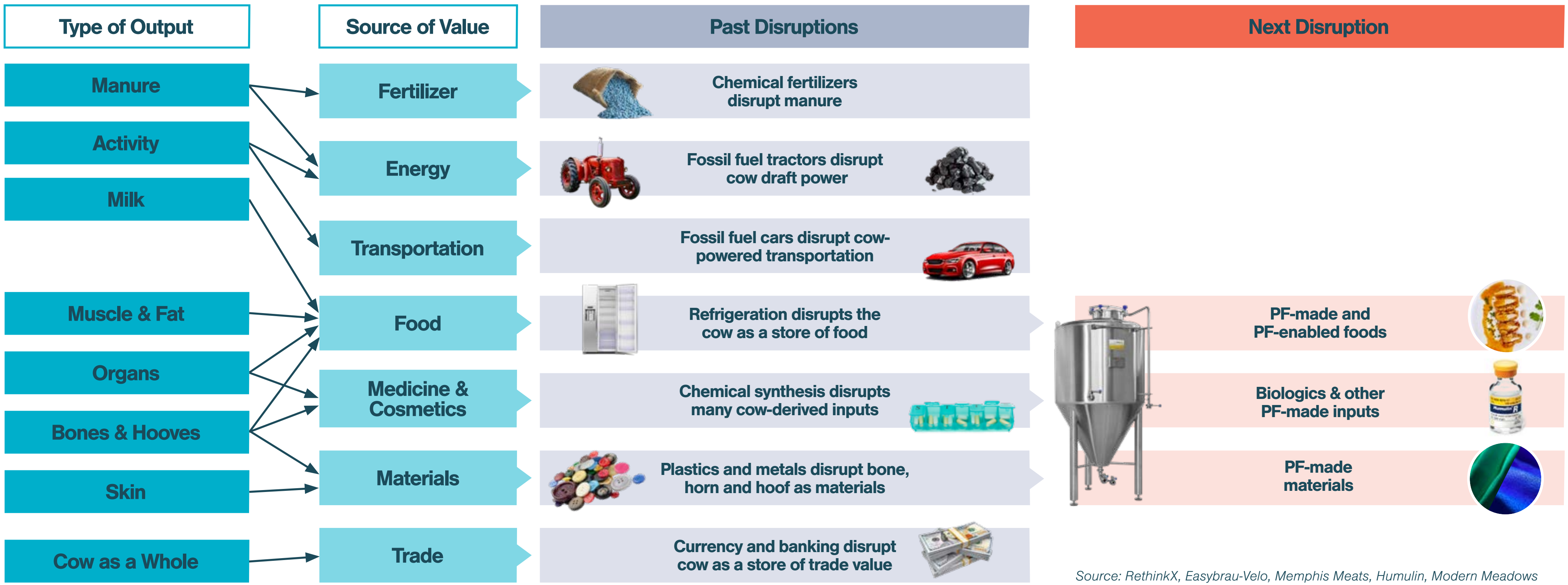
The first domestication of the cow provided our Neolithic ancestors with a number of value streams – food (meat and milk), clothing, tools, and energy. Cows were also valuable in agriculture as draft animals and produced manure to fertilize the fields. They provided ancient populations with resiliency by acting as a form of food storage through winter and lean times. Cattle were also used for transportation of goods and people and, at times, were valuable as a form of currency and a means of trade and exchange.

Technology has already disrupted most of these sources of value. Tractors made cattle obsolete as draft animals, while their value as food storage was disrupted by the refrigerator. Petrochemical fertilizers decreased the value of manure, while the horse and then the car destroyed the value of cattle as transport. Food is the last remaining major source of value, with materials a distant second.

The cow – one of the oldest, largest, and most inefficient food production systems in the world – is now experiencing its final disruption. The remaining parts of the cow with any significant value – namely meat and milk, but also leather and collagen – are being replaced by superior technologies, products, and services, all enabled by the continued engineering by humans of micro-organisms.

These disruptions are already underway and will hit tipping points within five years, accelerate through the mid-2020s and be over by 2035.

## Figure 6. Unbundling the Cow




*Source: RethinkX, Easybrau-Velo, Memphis Meats, Humulin, Modern Meadows*

# 2.2 The Disruption of the Cow

## 2.2.1 Proteins: The Disruption Starts Here

As we have seen, proteins produced by modern food production methods are already used in healthcare, vitamins, and cosmetics. They are now beginning to disrupt major, recognizable portions of the wider food market. We already eat many foods with ingredients produced by PF, yet very few of us are aware of it. These include valencene (orange taste and smell), raspberry aroma, sweeteners like thaumatin, and vitamins, as well as a number of enzymes used in food processing like rennet, amylase, or lipase (see Box 7). More recently, the process is being used to make soy leghemoglobin (heme).[30] Many of these products have already completely disrupted the markets they entered.

The next proteins to be disrupted are those produced by cows, namely those in milk and meat. They will instead be created directly from micro-organisms rather than extracted from the cow (the macro-organism). These individual proteins will then be built up to make the end product, whether it be ground meat, a burger, or a steak. This is a complete reversal of conventional production methods, where the cow is broken down into constituent components and then processed according to which end product is desired. In the conventional system, single molecules such as whey are the hardest and most expensive to produce. In the new system, they are the easiest and cheapest to produce. Crucially, the single protein molecules made using modern production techniques will be superior, purer, and more consistent than those extracted from the cow.

## Box 7: PF Rennet in Cheesemaking

Rennet is an important group of enzymes used to produce cheese, as it facilitates the separation of the solid curds and liquid in milk. Rennet comes from the stomachs of veal calves, which secrete the enzyme so they can digest their mother's milk. As such, rennet can only be obtained from these very young animals – calves stop producing it at about 60 days old. In the 1970s, the growing popularity of cheese in the U.S. conflicted with a growing animal rights movement and a mounting distaste for killing newborn calves. This led to a downturn in the veal market and higher prices for rennet. Cheesemakers were forced to turn to alternative, but inferior, vegetable and microbial rennets that, by the 1980s, made up about 50% of the market.[31] Around the same time, a production method using PF was being developed to produce pure chymosin, the active ingredient in rennet, much more efficiently than through animal production and in a form that functioned better than the non-animal alternatives. Fermentation-Produced Chymosin (FPC) was approved for use in the production of food in 1990 and by 2012 it was used to make more than 90% of the cheese produced in the U.S.[32, 33]

## 2.2.2 The Four Waves of Disruption

The disruption of the cow is not just a simple one-for-one substitution – a conventional sausage or burger replaced by a novel alternative (though that will happen). New production methods only need to disrupt key ingredients, not entire products, in order to render the cow entirely redundant.

The direct, end-user product substitution is, in fact, just one of four main ways in which the cow will be disrupted over the next decade and beyond. All of these disruptions overlap, reinforce, and accelerate one another. They fall into two broad categories:

### What we eat:

1. **Substitute ingredients.** The one-for-one substitution of animal-derived ingredients with those made using modern production methods. This is a business-to-business (B2B) disruption, where consumer preference is not a key driver.
2. **Substitute end products.** This is a business-to-consumer disruption:
   - » Proteins produced using new production methods are mixed with other ingredients to form the end product. This is not, therefore, a one-for-one substitution.
   - » Cell-based meat enabling the one-for-one substitution of complete, complex food products made from animals.

### The way we eat:

3. **Fortification.** The addition of ingredients made using modern production methods to existing food products.
4. **Form factor.** The replacement of existing forms of food with entirely new forms.


*Source: Bulletproof, Chief. Collagen, Caveman Foods*

### 1. Substitute Ingredients

This is the one-for-one substitution of animal-derived proteins and other ingredients that usually represent a small percentage of the final product. For example, the replacement of whey protein in sports drinks or baby formula, or of gelatin, a common ingredient used as a thickener in both sweet and savory dishes.

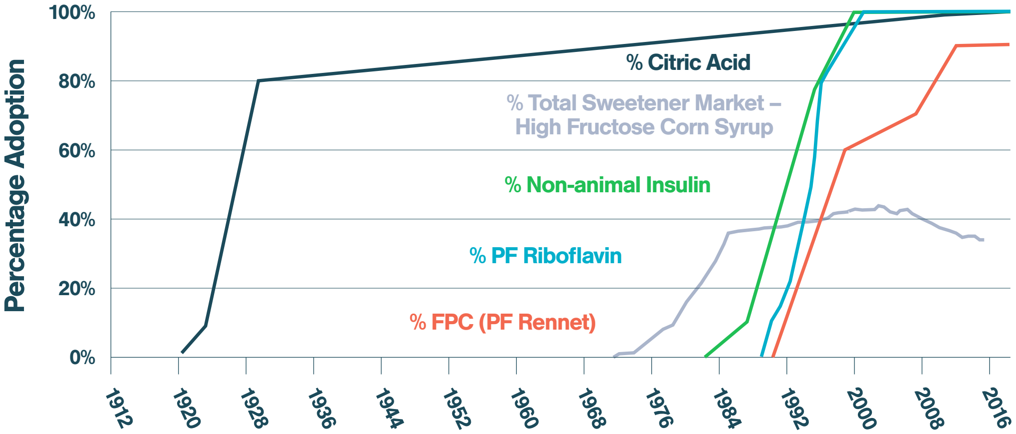
Decisions to use these ingredients, many of which are key components of products despite being used in small quantities, will be made by businesses, not consumers, based on lowering cost (buying cheaper ingredients or increasing the product shelf life), risk mitigation (such as the reliability, consistency, and quality of supply), and the ability to increase revenues (for example by increasing the value to customers through higher protein or superior nutritional content, or by highlighting a healthier, more sustainable, or animal-free product).

As we have seen, some of these B2B ingredient disruptions can happen very quickly (see Figure 7 below).

For example, HFCS 55, a sweetener with 55% concentration of high fructose corn syrup, was introduced in 1978. The wholesale price of refined sugar spiked twice in the 1970s[34], leading Pepsi Cola and Coca Cola to start replacing sugar, their key ingredient, with HFCS-55 in 1980. By 1984, all of their soft drinks bottled in the U.S. used HFCS-55 instead of sugar.[35]

This direct substitution is a B2B disruption, which means that consumer preference is not the primary driver of adoption.

## Figure 7. Food Ingredient Disruptions Happen Quickly and Follow S-curves




*Source: RethinkX, Citric Acid: Ciriminna et al., 2017, Berovic & Lesiga, 2007, Max et al., 2010, HFCS: USDA, Insulin: Leichter, 2003, Lipska et al., 2014, Riboflavin: Ruevelta et al., 2016, FPC: The Vegetarian Research Group, Persistence Market Research, Business Wire, Hellmuth, 2006*

### 2. Substitute End Products

*Mixed Ingredients*

This is where PF-produced proteins are mixed with other ingredients to form the final end product. This will happen in the dairy, meat, and leather markets. We refer to these products as PF-enhanced – where PF proteins are part of a broader list of ingredients such as plants and mycoprotein (a single-celled fungal protein grown by fermentation). For meat, PF enables the production of molecules like heme, which, when combined with other ingredients, allows the production of a ground meat replica that improves upon the animal-derived original in ways that plant-based, non-PF alternatives simply cannot.

This is the approach taken by Impossible Foods in the production of their Impossible burgers, which have sold more than 13 million units since they were launched in 2016.[36] Because the attributes of these new products will be superior to animal-derived products on every parameter, businesses are likely to introduce them as product line extensions that offer additional benefits. Burger King has done just this, introducing the Impossible Whopper as part of its Whopper brand. The company initially priced the burger at about $1 more than the conventional Whopper while promoting its health benefits.[37]

The milk industry provides an excellent example of how this mixed ingredient disruption will play out.

*The Disruption of Milk*

The milk industry is currently on a knife-edge – it operates on extremely thin margins[38] and suffers from volatile commodity prices,[39] and so relies on government subsidies[40] and support from powerful lobbying arms to stay afloat.[41] Cow milk shows very well how only a small percentage of ingredients need to be replaced for an entire product to be disrupted, triggering the collapse of an entire market.

Solid proteins (casein and whey) account for just 3.3% of milk's overall composition. The rest is made up of 87.7% water, 4.9% sugar (mainly lactose), 3.4% fats, and 0.7% vitamins and minerals.[42]

The key to understanding the disruption of milk is that PF only needs to disrupt 3.3% of the milk bottle – the key functional proteins – to bring about the collapse of the whole cow milk industry.

## Figure 8. Molecular Composition of Milk

**The key to understanding the disruption of milk is that PF only needs to disrupt 3.3% of the milk bottle – the key functional proteins – to bring about the collapse of the whole cow milk industry**


*Source: RethinkX*

Roughly 65% of milk proteins are consumed directly, either as drinking milk or in dairy products like cheese, yogurt, and ice cream.[43] The remaining 35% are consumed indirectly as ingredients in all manner of products, from cakes and desserts to baby formula and sports supplements. These ingredients will be the first to be disrupted.

**The disappearance of a third of industry revenues will be enough to push the primary milk production industry into bankruptcy**

Whey and casein proteins have become universally available and are widely-traded commodities.[44,45] Both are already being targeted for production through PF.[46] We anticipate these PF proteins will reach cost parity with their animal-derived equivalents by 2023-25, with the marginal cost converging over time towards the cost of sugar (less than 10¢/kg) plus water and energy.[47]

But disruption history indicates that price parity does not have to be reached for these products to be adopted. Initial adoption will come when the proteins offer a superior product by offering something cow milk proteins cannot. For example, baby formula currently uses cow proteins, but the possibility of using PF to make human breast milk proteins should provide a superior product in terms of toleration and nutrition.[48] Improvements in other areas such as better adaptability, more consistent quality, lack of price volatility, and security of supply will also spur businesses to use these PF products.

As protein consumption switches to these modern alternatives, the 35% of the milk market that is used as ingredients will disappear rapidly. The disappearance of a third of industry revenues will be enough to push the primary milk production industry into bankruptcy.[49]

But the disruption does not end there – the rest of the milk protein market will soon be at risk. Dairy products like cheese, yogurt, and ice cream will also be manufactured using superior and cheaper PF-based proteins.

The disruption of whey proteins will be a key catalyst in the process. Today, regulated dairy producers get compensation for whey – whether there is a market for this protein or not.[50] Whey is a byproduct of cheese production that brings incremental revenues to large cheese manufacturers. As PF whey disrupts cow whey, they will have to join small cheesemakers (who do not have access to the dry whey market) and lose money disposing of whey.[51] As the additional revenue streams generated from this protein fall, industrial cheese prices (and government subsidies) will have to rise to compensate, thus lowering demand and accelerating the disruption of the market by PF-based alternatives (see death spiral in section 2.3). This will add a whey glut to the bulging cheese glut in the U.S. market.

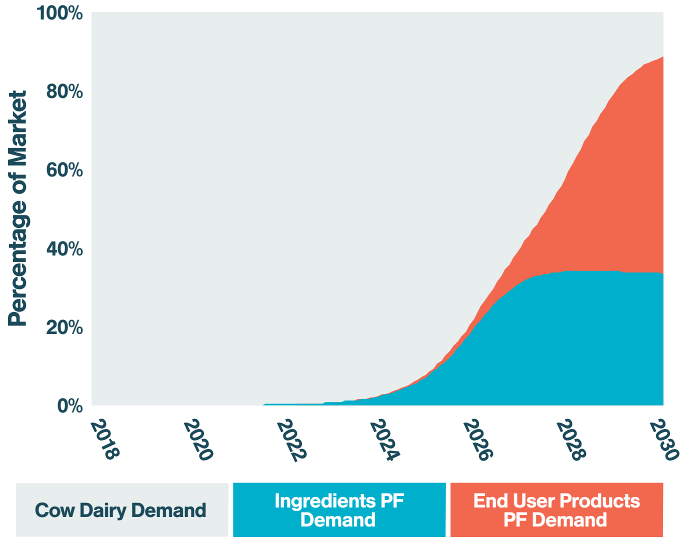
By this point, the only market left for cow milk will be drinking it. But even this market will soon be threatened as the underlying PF production processes continue to improve, including those for fats, vitamins, and minerals, the other key functional ingredients in milk. Finally, then, as replication and improvement of drinking milk becomes possible, this last market will be completely disrupted. Producers will be able to develop a lower-cost product that replicates the taste and feel but improves on other attributes, including tolerability, digestibility, and nutrition. Indeed, non-PF, plant-based milks already command a 13% market share in the U.S. despite a large price premium and a different taste profile.[52]

As demand for milk drops, milk processing costs will rise as economies of scale reverse and plants operating below capacity drive costs up. To stay in business, milk producers will have to raise prices, causing demand to drop further, accelerating the switch to modern production methods, which will continue to improve exponentially.

The wider dynamics of the food industry will also come into play. The milk industry does not operate in isolation – it is connected to the broader cattle industry through hides, carcasses, and other inputs like feed. The effects of disruption to these broader markets will act to accelerate the disruption of the milk market, and vice versa.

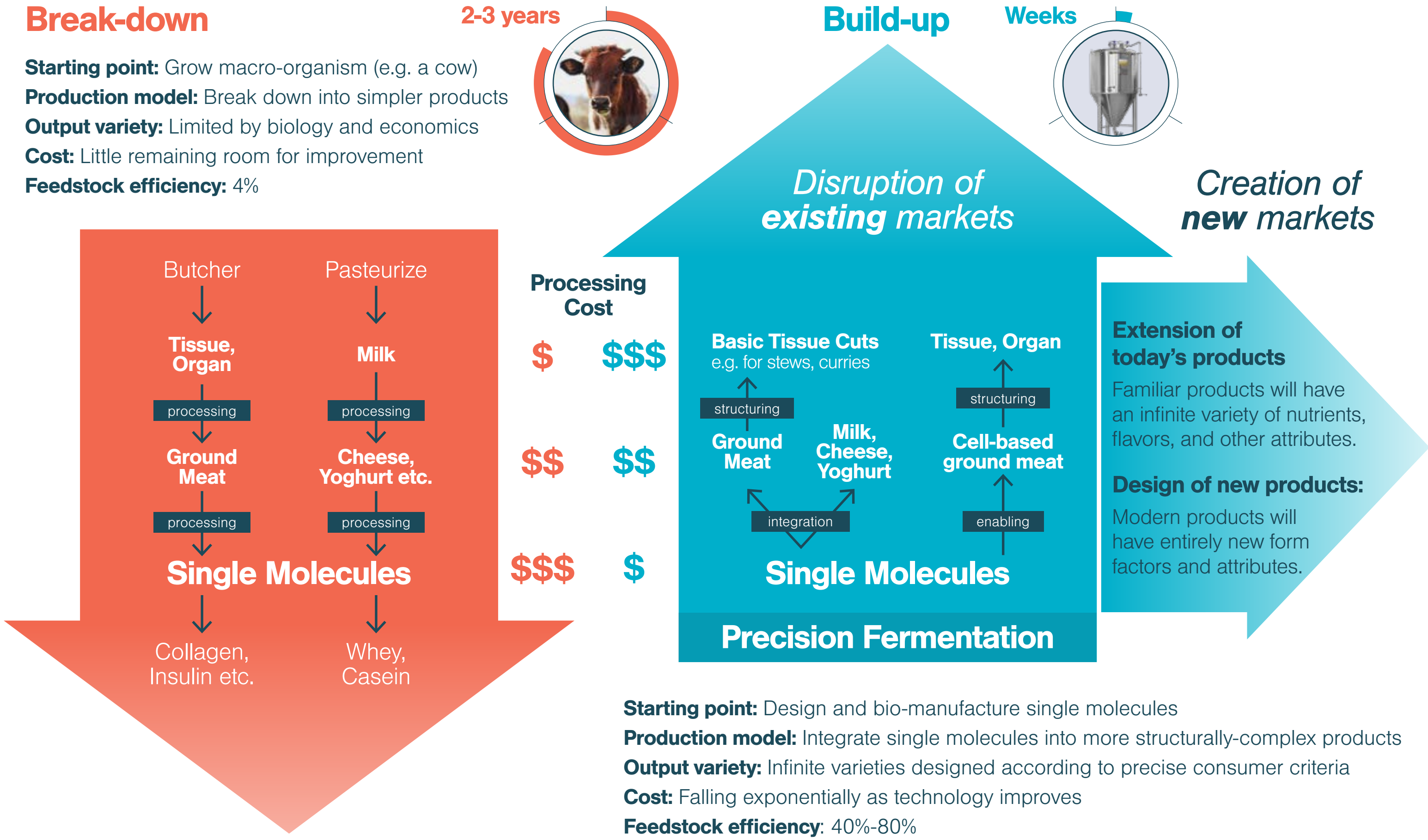
Ultimately, there is little the existing milk industry can do and, barring massive government bailouts, we expect to see widespread bankruptcies throughout the 2020s and the industry to collapse before 2030. **By 2030, we expect almost 90% of U.S. dairy protein demand to come from PF alternatives.**

**Figure 9. U.S. Dairy Protein Demand**




*Source: RethinkX*

# Figure 10. Reversing the Economics and Model of Food Production




**Starting point:** Design and bio-manufacture single molecules
**Production model:** Integrate single molecules into more structurally-complex products
**Output variety:** Infinite varieties designed according to precise consumer criteria
**Cost:** Falling exponentially as technology improves
**Feedstock efficiency**: 40%-80%

**The build-up model flips the production and economic models of food production on their heads:**

**Economics:** Single molecules are the simplest and cheapest outputs to produce using modern foods, with production cycles 100 times faster than growing animals. This is the opposite of today's break-down model of animal agriculture in which single molecules are the most expensive and difficult to extract. Conversely, complex structures are the hardest and most costly to produce using modern foods today.

**Production:** Food-as-Software product design and development means that modern foods and molecules are designed and developed like apps. Anyone, anywhere will have access to food design tools with vast on-demand, open source (as well as pay-per-use) molecular and nutritional databases that will allow them to design new foods (and cosmetics, medicines, and materials) that are built up and integrated according to designed criteria (e.g. nutrients, taste, and texture), and then downloaded to fermentation farms located across the street or around the world.

## Key Dimensions of Disruption

Modern foods will disrupt animal-derived foods along multiple dimensions in parallel, driven by their growing competitiveness in terms of cost and attributes.

### Structural Complexity

Simpler 2020 → More Complex 2030

Modern foods will disrupt products with simpler structures like ground beef before those with more complex structures, like steak.

### Concentration

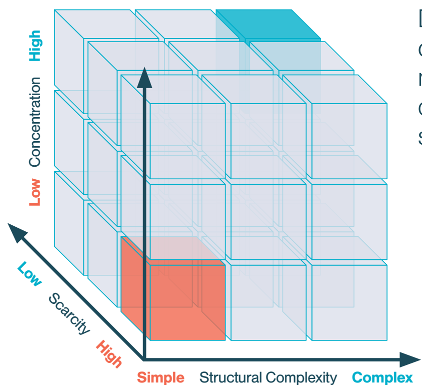
Lower 2020 → Higher 2030

Modern foods will first disrupt products with low concentration of key functional ingredients, such as milk (only 3.3% protein).

### Scarcity

Higher 2020 → Lower 2030

Modern foods will first disrupt products that are scarce in nature and difficult to extract (and therefore costly), such as insulin.




Disruption occurs along multiple dimensions simultaneously.

Source: RethinkX

# **Box 8:** Material Disruption

The disruption hitting the milk market is also being played out in other animal ingredient markets where PF will enable a superior and cheaper alternative to animal-derived products. These include the disruption of fabric, with spider proteins being made into thread for use in clothes,[53] and certain industrial products with proteins from rare or extinct animal horns or claws (which are often made from the protein keratin).[54] "Smart" fibers that glow in the dark, change color, or even diagnose medical conditions by detecting changes to the body will also be possible.[55]

A key market ripe for disruption is leather, via PF-produced collagen. Collagen is the most abundant family of proteins in animals and is present in skin, tendons, ligaments, bones, and teeth. It is the key protein ingredient in leather at about 30% by weight.[56]

Source: Spiber, The North Face

*Spider silk is by some measures stronger than steel. While you cannot domesticate territorial spiders to mass produce silk, nor synthetically replicate it at a competitive cost ($20-$30 per kilogram), you can program a microbe to produce it. This is the approach PF company Spiber has taken to design its Moon Parka in partnership with The North Face.*

The production of collagen through PF will allow the production of modern leathers, which will be a vast improvement on those that are produced from animals. No longer limited by the constraints of the break-down model, leathers of virtually any property become possible. Strength, size, flexibility, thickness, feel, aesthetics, texture, and durability all become variables that can be tailored to the customer's needs.

This will not be the first time animal leather has been disrupted – the 20th century saw the rise of artificial leathers synthesized from petrochemicals at a third of the cost. They now represent about two thirds of the overall leather market. More recently, entrepreneurs have also created leather materials from plants[57] and fungi,[58] but none so far can match all the attributes of animal leather. As the cost of PF continues to fall and the characteristics of the leather produced by it continue to improve, modern leathers are poised to surpass animal leather on every functional attribute. In fact, PF will not only disrupt the existing uses of leather, but also create new markets that conventional animal leather does not address, such as roof shingles or tiles.

**By 2030, we forecast that leather produced from non-animal sources is likely to have a 90% market share, while the collagen market in cosmetics and food is likely to be almost 100% disrupted.[59]**

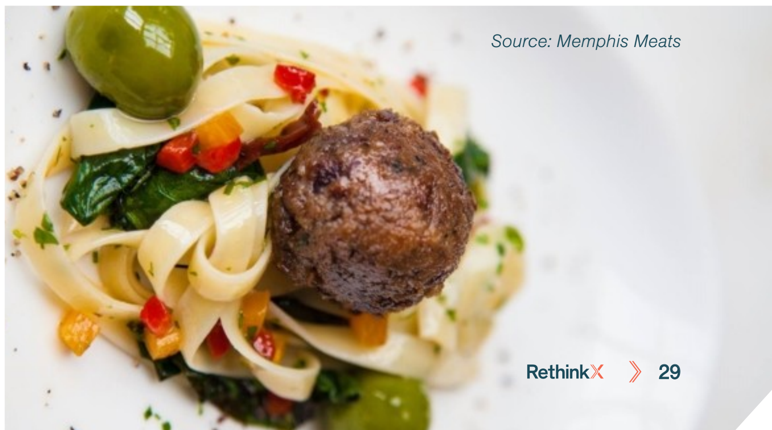
### *Cell-based Meat*

The disruption that most people instinctively think about is the one-for-one substitution of an existing product for a new one, such as burgers, sausages, ground meat, and steak. Initially, we see replacements coming from both PF-enhanced food (discussed above) and cell-based meat.

Cell-based meat is the direct, one-for-one substitution of complete, structurally complex food products made from animals. This is where the animal cells (mainly muscle and fats) are cultivated in a growth medium outside of the animal to create meat – animal meat without the animal. This is the approach taken by companies such as Mosa Meat and Memphis Meats.

The disruptions involving any kind of structural products will move more slowly than the single molecule ingredients, because these products are harder to develop due to structural complexity and the need to combine different types of molecules, such as fats and proteins.

Cell-based meat is a fundamentally different disruption to PF, with its own cost curve (just like PF, the costs of cell-based meat production are falling rapidly), adoption rate, and regulatory approvals. However, cell-based meat may have a distinct advantage from a consumer perspective because it is animal meat. Conceptually, consumers may feel more comfortable with this.



Source: Memphis Meats

*The Disruption of Beef*

*The Ground Beef Market*

Ground meat is the most significant and ubiquitous beef product, representing 40%-60% of the output of a cow by volume.[60] It can be used in a variety of ways, from burgers and meatballs to sausages and lasagnas. Structurally, it is a far easier product to replicate than animal tissue.

Analogue meat products are not a new phenomenon – products like seitan, tempeh, and tofu[61] have been around for centuries, with more recent products like the mycoprotein-based Quorn[62] and purely plant-based alternatives such as textured vegetable protein introduced decades ago. However, their taste and texture has not been good enough to convince meat eaters to switch in meaningful numbers. Modern foods mean that, for the first time, new alternatives are now more than good enough.

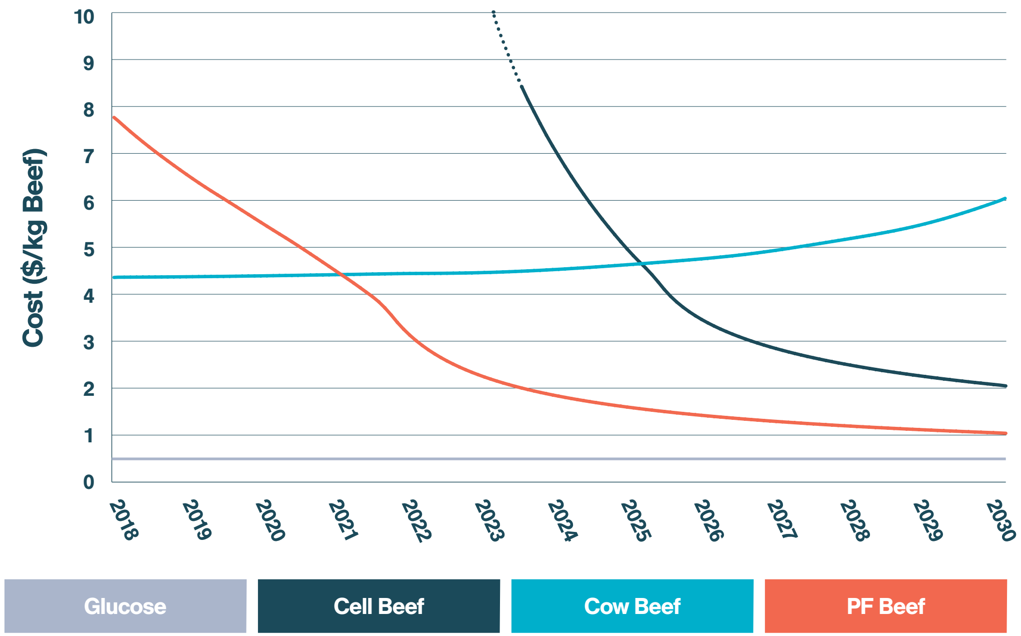
There are already a number of PF-enhanced products on the market, such as Impossible burgers, that can compete with animal-derived ground meat, some with significant advantages such as health benefits and the ability to introduce new flavors.[63] Adoption has begun before price parity is reached as many consumers value these non-cost benefits. Once price parity is reached, we believe between 2021 and 2023, disruption becomes inevitable. Like the milk market, the beef industry operates on thin margins and just a small fall in demand is needed to trigger widespread bankruptcies and the collapse of the industry (see death spiral in section 2.3).

While we expect PF-enhanced meat to be cheaper than cell-based meat in 2030, the cost ultimately depends on the make-up of the final consumer product – for example, a pure cell-based burger may not be intrinsically superior to a mixed PF/cell-based burger, and every product could have a different profile.

This is already happening today – the first products on the market are not 100% PF-enhanced burgers, but mixes, such as the 2% heme Impossible Burger. Once costs fall, the Food-as-Software model will ensure that more of the burger will be made with PF. This will be more heme at first, then more protein and more of the fats. The first cell-based products, which we believe will hit the market in 2022 before reaching cost parity with conventional ground meat in 2025-26, are likely to follow the same pattern. This means the disruption of the ground meat market will happen far faster than mainstream analysts believe. In fact, foods using ground meat as just one of a number of key ingredients, such as lasagna and spaghetti Bolognese, may be disrupted before burgers. By 2030, therefore, we expect a 70% reduction in the market for animal-derived ground beef in the U.S.

**By 2030, we expect a 70% reduction in the market for animal-derived ground beef in the U.S.**

## Figure 11. Cost Curves for Beef




*Source: RethinkX*

**By 2030, we expect a 30% reduction in the market for animal-derived tissue beef in the U.S.**

*The Tissue Beef Market*

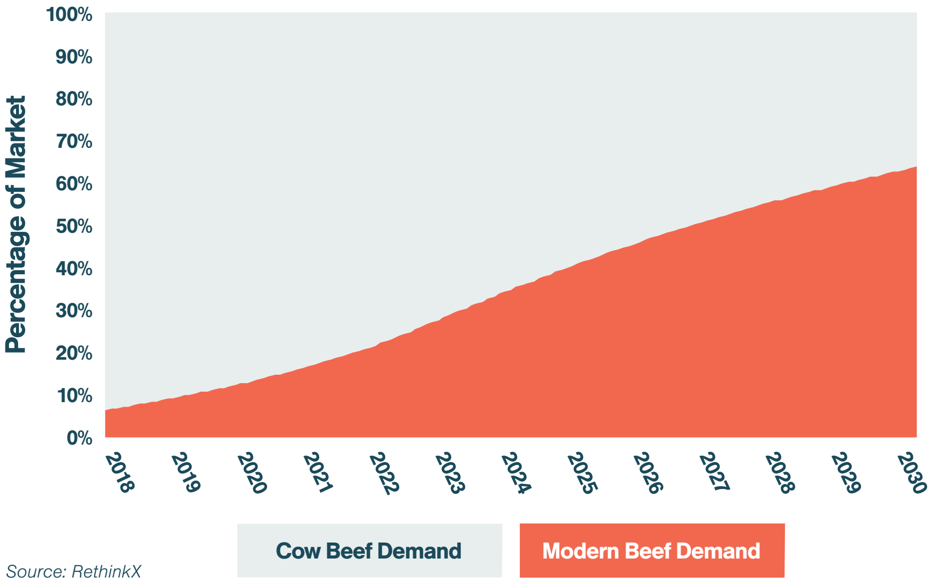
The drop in the cost of ground beef and the rising cost of steak (see death spiral in section 2.3) will increase the price differential between ground meat and steak, leading to a switch in demand from steak to ground meat. While producing a steak is the hardest challenge for modern food production technologies, we expect competitive steak alternatives to enter the market by the late 2020s. The earliest versions are likely to be used in stews or curries that require lower quality cuts of meat.

By 2030, we expect a 30% reduction in the market for animal-derived tissue beef in the U.S. This will come from a combination of direct replacement of steaks alongside a shift from tissue to ground meat consumption, together with the impact of the fortification disruption (see below).

*The Overall Beef Disruption*

**By 2030, therefore, we expect 70% of all beef consumed to come from modern production methods** (see Figure 12). PF-enabled beef alone will replace 55% of the beef market, which means **we do not need cell-based beef for the cow to be completely disrupted.**

## Figure 12. U.S. Market Share of Cow vs. Modern Beef Products




*Source: RethinkX*

## Box 9: The Importance of Pet Food

The pet food industry is extremely important to the U.S. livestock system, as many products that typically go into U.S. pet foods are not considered fit for human consumption and would otherwise be waste.[64] The $24bn pet food market accounts for about a quarter of America's total animal-derived calories.[65] In fact, 160 million pets in the U.S. consume so much meat that, if they were their own country, they would be the 5th largest consumer of meat in the world.[66,67] The important components of a nutritionally-balanced pet food, like proteins, fats, and vitamins, can be made with PF or cell-based meat. Pet food is an ideal market entry point because the products are more flexible with ingredients and product form, which can be difficult to perfect. Cat food, for example, could be a mixture of mouse or squirrel cells and proteins.

The pet food market is likely to be the first where cell-based meats are widely used and, because of its size, it will take material profits away from the animal-derived meat industry, thereby accelerating the wider disruption.[68]


*Source: Wild Earth*

### 3. Fortification

As the price of modern proteins drop at the same time as their functionality improves, they will be increasingly used to enhance all kinds of food products. We call this fortification.

We have already seen this happen without modern production methods – the number of new products with added protein doubled from 2013 to 2017.[69] These fortified products, such as protein cookies, chips, water, and fruit juices, are commonplace on grocery market shelves. Other products like 'super-milk' with added proteins and fats, which is increasingly popular among baristas due to its creamier froth, are also finding a market.

In fact, the most successful new consumer food or drink product in the U.S. in 2017 was Halo Top, a startup company that launched an ice cream with more than twice as much protein as regular ice cream.[70,71] A pint of vanilla Halo Top has 280 calories, 8 grams of fat, 12 grams of fiber, and 20 grams of protein.[72] Halo Top now turns over more than $350m a year in revenues.

Cheaper, more versatile proteins made by modern production methods will mean this market will grow substantially in the coming years. By 2030, we estimate that 10%-20% of total protein consumption in the U.S. will come from nutritionally-fortified products.

Half of this amount will come from increased protein consumption, and half will displace existing demand for animal protein, leading to a reduction in demand for animal proteins of 5%-10%.

Elsewhere in the world, where protein consumption is lower but growing towards Western levels (for instance in China), we expect fortified products to capture a greater share of the market. More than 90% of China's population and 70%-80% of African and South Indian populations are believed to be lactose intolerant.[73] In these markets, the lower cost of modern alternatives will drive a faster adoption as there is less attachment to conventional forms of protein.

### 4. Form Factor

Modern production methods will open up the possibility of creating entirely new forms of food. Indeed, how we consume food will change just as much as what we eat.

This should not be entirely surprising as food form factors have changed throughout history – the burger, now seen as the ultimate traditional American staple was a new form factor when it was first produced in 1921.

What may be surprising is that the best performing stock this millennium is not a social media, smartphone, or software-as-a-services company, but Monster Beverage, a producer of energy drinks with a number of added ingredients including sugars, salts, vitamins, and plant extracts. Since its 2003 IPO, the company's stock has gone up 60,000%.[74] And it is not alone – the energy drinks sector barely existed in 1999, but between 2000 and 2013 sales grew by 5,000% and it is now almost as large as the coffee market in the U.S.[75]

> **By 2030, we estimate that 10%-20% of total protein consumption in the U.S. will come from nutritionally-fortified products**

The same can be said of protein bars, which first appeared in 1986 with the PowerBar. By 1998, the nutrition bar industry had grown to $200m before growing another 1,000% on its way to $2.1bn by 2012.[76,77] Crucially, two thirds of nutrition bar consumers eat them as a meal replacement. Protein bars pack a combination of convenience, cost, nutrition, taste, and texture into a totally new form factor. We have seen the same story play out with protein powders, which followed a similar trajectory to become a $4.7bn market by 2015.[78]

Indeed snacking is becoming increasingly popular – 94% of Americans snack at least once a day,[79] while 50% snack two to three times a day. There is no reason to assume, therefore, that the traditional convention of sitting down to a meal three times a day, or even just once a day, will continue to be the norm.

There are even products available today that allow us to drink our food on the go. Soylent is an example of a new breed of technology company creating new form factors aimed at replacing meals completely. Its 'breakfast replacement' product is a 14-ounce (414 ml) drink with 150mg of caffeine (equivalent to a 16-ounce Starbucks grande latte),[80] 20 grams of protein (equivalent to more than three eggs),[81] 500mg of Omega-3 (equivalent to a 6-ounce can of tuna)[82] and 26 essential nutrients, all for $3.25. Today, Soylent's products are sold on Amazon and in 20,000 retail stores including Walmart, Target, and 7-Eleven.[83] Disruptive companies like this are not bound by conventional assumptions about how food should look and taste – they do not respect the artificial boundaries dictating that protein is a solid animal, which is separate from a liquid coffee, which is separate from a multivitamin pill.

New modern food technologies will take this form factor disruption a step further. As we are freed from the biological constraints of livestock evolution and its extractive, break-down model, we will be able to meet our nutritional requirements in any conceivable form. Our imagination and a molecular chef's ability to realize its vision are the only limits.[84]

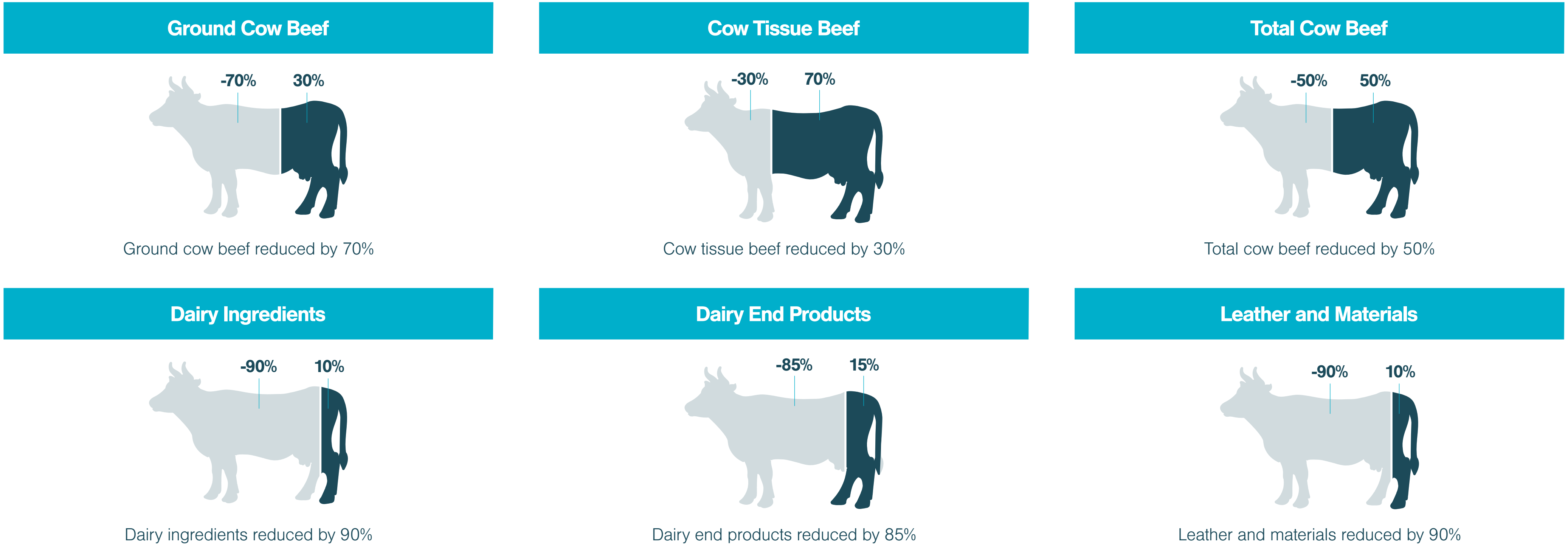
Food will be personalized to the consumer's form and nutritional needs. Picture a 'Nutrition capsule' or even a 'Full Meal pouch' that can be brewed like coffee at a supermarket, restaurant, or even at home. Just like we brew Colombia, Indonesia, or Guatemala coffee pods, companies could develop a Paleo, Keto, or Smart nutrition capsule.

In this report, we are not including any reduction to animal meat demand from the form factor disruption but, beyond 2025, we see a high likelihood that this disruption will impact a material and ever-growing part of the food market as modern food entrepreneurs and molecular chefs invent entirely novel ways to produce, distribute, and consume the foods we eat.

## 2.3 Adoption Dynamics: How Far and How Fast?

These four waves of disruption will reinforce and accelerate one another, so that modern foods rapidly begin replacing animal-derived products. The disruption has already started and once certain tipping points are reached, adoption will accelerate exponentially. As modern products get cheaper and more capable, a virtuous cycle will be triggered, speeding up adoption across every key market. At the same time, as animal-derived products become more expensive and less attractive relative to their modern equivalents, a vicious cycle will be triggered, hastening the demise of industrial animal food production.

### Figure 13. Cow Use in 2030 Relative to Today

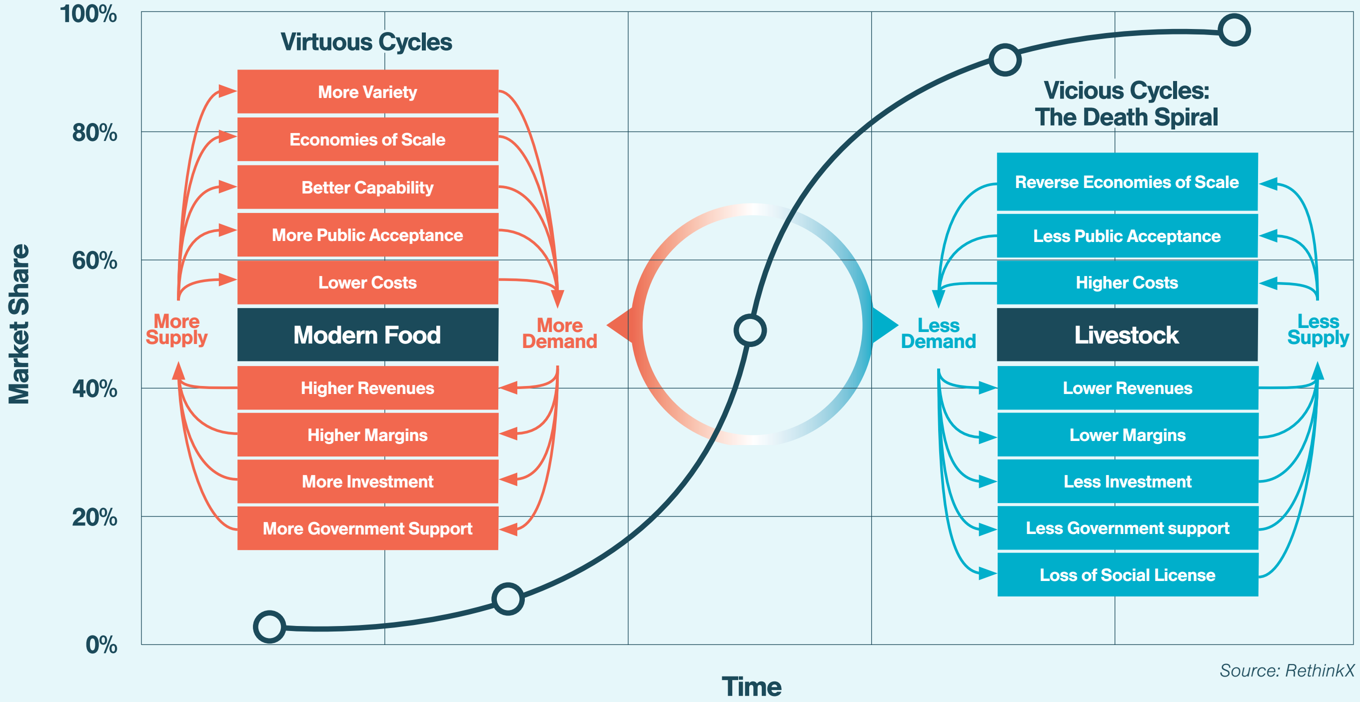



*Source: RethinkX*

# Box 10: The System Dynamics of Disruption

The disruption of food and agriculture, like all technology disruptions, will be a non-linear process of change, following an S-curve – adoption appears to begin slowly and then accelerate exponentially, before slowing again towards market saturation (see Figure 14). In reality, adoption is always exponential. The process of adoption is driven by feedback loops, both self-limiting (brakes) and self-reinforcing (accelerators). In the early stages of disruption, there is resistance to change as the accelerators struggle to overcome the brakes, but, as new products are developed and come to market, the accelerators begin to overwhelm the brakes and adoption takes off.

## Figure 14. Feedback Loops




Source: RethinkX

### Virtuous Cycles

Increasing demand for modern foods will drive increasing economies of scale, increasing investment of money and ingenuity, leading to ever-greater improvement in cost and capabilities, driving further increases in demand. Feeding into this cycle and driving demand ever higher will be greater public acceptance and, therefore, appetite for modern foods, and greater government support as the significant advantages they hold over animal-derived products become clearer.

Given its biological limitations, the industrial agriculture industry will be unable to compete, especially so once the death spiral sets in.

### Vicious Cycles: The Death Spiral

As demand for animal products is chipped away by modern alternatives, we will see the industrial system of meat production coming under ever-increasing pressure.

Milk, hides (for leather), collagen, gelatin, and ground and tissue meat will be replaced by lower cost, higher quality modern substitutes. At a certain tipping point – we estimate at 10%-15% of the market[85] – the incumbent industry will enter a vicious cycle. As the various cow product markets begin to be disrupted, prices of the remaining products will jump as the full costs of production and processing will need to be borne by an ever-smaller number of products that still have markets available to them.

This price spiral and continuing reduction in demand will ultimately lead to the value chain breaking down as abattoirs, renderers, processors, and packagers see decreasing utilization and hence reversing economies of scale (see Part 3). Eventually, they will be forced to shut down as their economics continue to deteriorate. The beef and, especially, dairy industries operate on extremely thin margins, with high operating and financial leverage, and are propped up by government subsidies. Both are already hanging in the balance and just a small drop in demand will send them spiraling towards bankruptcy. While continued government support is certainly possible, the bill will continue to rise and is not sustainable in the long run. Furthermore, clean-up costs for industrial feedlots and processing plants will make shutting down an expensive option, and these costs are likely to be passed on to taxpayers if the businesses that operate them fail.

**This means that the disruption of the cow will be irreversible well before the new technologies are capable of producing the perfect steak at a competitive cost.**

## 2.3.1 Key Stakeholders' Role in Adoption

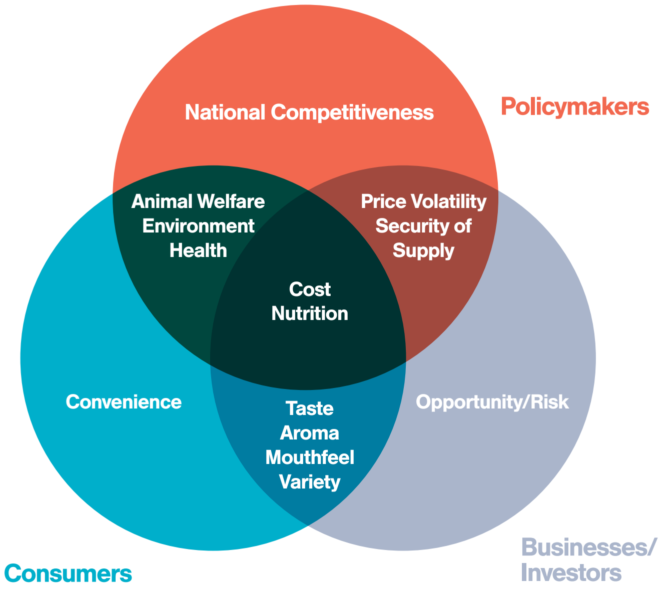
There are four main agents that could accelerate or slow down the modern food disruption – consumers, businesses, investors, and policymakers. These groups are interdependent – the actions and choices made by any one group affect those made by all others.

Different stakeholders will be driven by different combinations of factors. For individual consumers, cost, taste, and convenience are the most important. For businesses, cost, revenue, and risk mitigation are key. Meanwhile, governments and states can help or hinder the incumbent and disruptive industries through regulation, tax, or subsidy, depending on how beneficial they are to the economy, the environment, and society. Lobby and interest groups will also play an important role in influencing them.

### Consumers: Embracing Change

Because modern foods are superior to animal-derived products, we expect to see their adoption begin as soon as they are available, and well in advance of cost parity being reached. Indeed, this is borne out by the enthusiastic early adoption of many products that have recently entered the market, such as Impossible burgers.

**Figure 15. Factors Influencing Decision-makers**




*Source: RethinkX*

According to the diffusion of innovation theory, whenever new products enter a market they are met with different reactions depending on the individual consumer.[86] All technology innovations face an initial level of excitement from some and skepticism from others. But history has taught us that this resistance is never as deep rooted or intransigent as we may think. This has been the case for every major technological disruption of the past century and more, whether it be the car, the television, or the internet – the speed of adoption of new technologies always takes us by surprise.

More recently, ride-hailing has been embraced by consumers and is now a mainstream service less than 10 years after launching. Part of its rapid rise is the fact consumers can easily try it with minimal effort, cost, or risk (high trialability). At first, the new service is an alternative to their main means of transport (whether taxis, car ownership, or public transport), but, the more they try it, the more they appreciate its advantages. Before long, it becomes their main form of transport. We believe modern foods will follow a similar pattern, but resistance will crumble even faster because they will be so easy and cheap to try[87] – there is no long-term commitment and consumers can use modern products to meet some nutritional needs and continue to use conventional products to meet others.

Perception, therefore, is a variable, not a constant. Over time, this change in perception will drive the 'social license' feedback loop. The industrial livestock industry imposes many costs on society (externalities) that are not borne directly by the industry.[88] These include health costs that come from eating meat (obesity, diabetes, heart disease, and cancer), the impact of livestock on the climate, on antibiotic resistance and foodborne diseases, and on animal welfare.[89] These are generally tolerated because governments prioritize the need for low-cost and secure food supplies. But, for the first time, the emergence of a genuine alternative – a new food system that produces lower cost and superior food and that imposes a fraction of the externalized costs on society – means that these externalities are unlikely to be tolerated by the public. The social license will move from animal-derived foods to modern foods. This will create the political space for policy and regulation both to support the modern food industry and, potentially, to penalize animal-based food production.

## Box 11: Overcoming Resistance

New technologies often face a high bar to adoption that comes from the lock-in of the existing system. Skeptical consumers can be an important part of this lock-in, but there are many others. Supply chains are well established, bringing economies of scale to production, processing, and distribution, while regulation, legal, and fiscal frameworks, including standards, approvals, labeling laws, and subsidies, are in place for existing products. Modern foods have to overcome these barriers.

Furthermore, the prospect of disruption can trigger further resistance from businesses or workers threatened by it. We already see clashes over the labeling of PF meats and over the approval standards required for them. We expect to see further battles emerging over subsidies to both old and new products, over the process of approval, and over public opinion – with scare stories or phony science used to discredit modern products. The farming lobby, for example, exerts a powerful influence in the U.S.

However, all these barriers are variables, not constants. They can initially appear insurmountable but, over time, the influence of the old industry diminishes while that of the new increases. Barriers are soon overcome and adoption occurs far faster than most contemporary observers expect.

### Businesses and Investors: No Production Constraints

As modern products enter the market and scale up, there are few production constraints. The inputs into their production (DNA, feedstock, energy, and water) are, and should continue to be, available in abundance, particularly given the massively-more efficient production processes used. Production capacity, which is driven by investment, represents the sole limitation on the supply side. But given the scale of opportunity and trajectory of investment already in the market, this is unlikely to be a constraint. Indeed, the emerging industry could benefit from repurposing existing infrastructure for the production of biofuels that will no longer be required as demand for them collapses during the move to on-demand, electric, autonomous vehicles (see Rethinking Transportation).[90]

*In 2019, Beyond Meat became a publicly traded company and rapidly grew to $10bn in market capitalization in the first few months of trading*


*Source: Beyond Meat*

Businesses and investors will face incentives to rush into this emerging market, driven both by the risk of disruption to their existing businesses and the opportunities that are emerging in new markets. This process is already playing out as companies such as Cargill and Tyson Foods are beginning to invest in disruptors. Indeed in the five years leading up to 2018, $17.1bn (including a $12.5bn acquisition of WhiteWave by Danone in 2017) has been invested in plant-based food and a further $73.3m in cell-based meat companies, with $720m invested in 2018 alone.[91,92] In early 2019, plant-based meat firm Beyond Meat went public with an initial public offering price of $25, before shares soared 550% in the first month of trading.[93] While Impossible Foods is still a private company, as of May 2019 it was valued at $2bn.[94]

### Policymakers: Global Competition

Policy choices matter. Decisions by regulators and legislators can both speed up and delay disruption and play a key role in defining the structure and dynamics of the market that emerges. This is particularly the case with food, where the farming industry is exerting, and will continue to exert, considerable influence in the U.S. to counter what it sees as an existential threat. The key areas in this battleground include intellectual property rights, ingredient approval, subsidies, and labeling (see policy recommendations in Part 4).

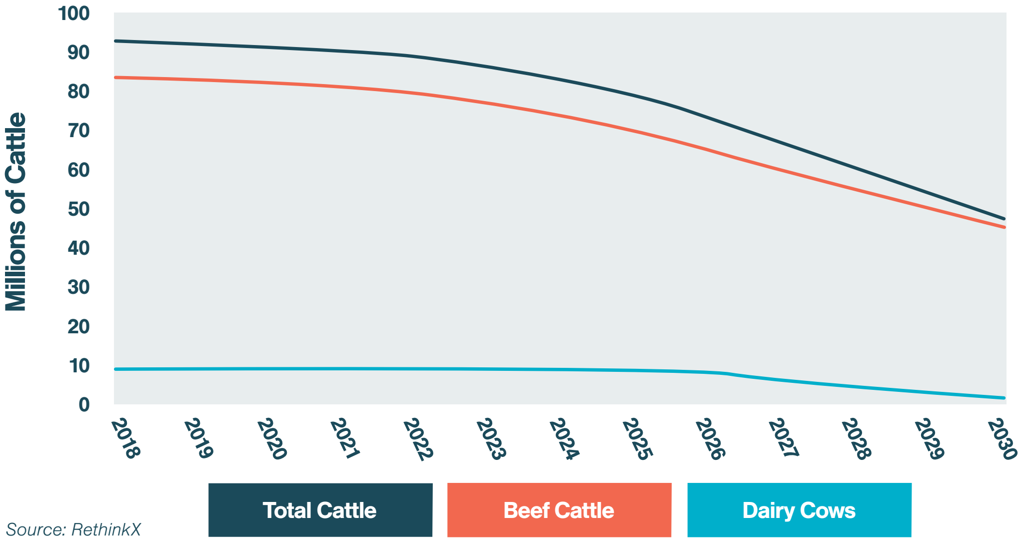
For the purposes of our adoption analysis, we assume a benign policy environment with little direct government influence to either speed up or slow down adoption. However, an aggressively supportive policy environment could accelerate the speed of adoption, while an aggressively obstructive environment could slow it by up to five years. In a globally competitive world, any active resistance has limited impacts – if the U.S. resists, other countries such as China will continue to drive development, forcing the U.S. to catch up. Equally, support or subsidy for incumbent industries will become increasingly expensive, weighing heavily on limited government finances and ultimately forcing a change of policy.

# 2.4 Key Conclusions

Our analysis takes into account the various waves of disruption (apart from form factor) and the virtuous and vicious cycles that we describe in the previous section and analyzes their impact on the market. We model three separate adoption curves for supply (when are products available and how quickly production can scale), demand (how quickly consumers will buy these products) and regulation (when these products will be allowed) for each of the markets. The combination of these gives us our central adoption case and the resulting number of cows reflected in Figures 16 and 17 below.

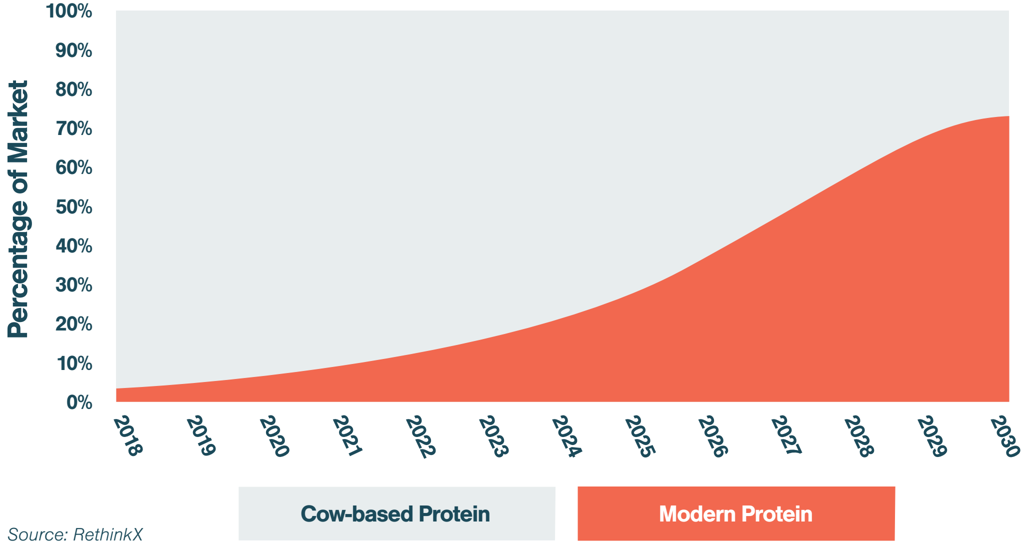
**We forecast the number of cows in the U.S. will have fallen by 50% by 2030, by which time modern proteins will have 75% of the cow-based protein market. By 2035, the number of cows will have fallen by 75%.**

**Figure 16. Number of Cows in the U.S.**




*Source: RethinkX*

**Figure 17. Modern Protein Market Share**




*Source: RethinkX*

# 2.5 The Disruption of Other Livestock

We have focused on the disruption of the cow in detail because, of all the food production systems, it is the most inefficient (and hence highest cost) with the most profound impact on humanity. But the same technologies disrupting cattle farming and its byproducts will also disrupt other livestock, such as pigs, chicken, and fish. While there are differences in relative efficiencies, the step-change improvement in cost and capability of modern production methods means that none of these markets will survive intact.

Research, development, and technological advancement in one species or product category will improve the underlying technologies and accelerate the disruption across all others. Because of its Food-as-Software capabilities, a company that makes modern burgers can easily make modern pork, chicken, or fish. The disruption process will be accelerated even further by improvements made to these technologies in the production of novel materials outside the food industry.


*Finless Foods is working towards the commercial launch of cell-based fish products*

*Source: Finless Foods*

Equally, the value chains of all livestock species are interconnected – livestock animals consume the same basic food products and resources and go through similar processing and distribution channels. For example, changes to the price of feed can occur either from exogenous events (natural disasters, drought), or from changes in demand from other livestock industries or for biofuels.[95] Once changes occur in one industry and affect the economics of feed, the knock-on effects will impact the profitability of other livestock industries.[96]

The disruption of other livestock will, then, proceed in a similar fashion to the cow, but different value chains and different regulatory environments across different species will mean that timing, order, and impact may vary. We anticipate the order will depend on three factors – efficiency of the industry, the proportion of products going into ingredients, and the extent to which regulation will protect incumbent producers.

For example, the egg industry, which is separate from chicken meat production, is relatively efficient compared with other livestock farming. At least 30% of eggs end up as ingredients in other food products[97] – each part of the egg serves a different purpose such as gelling, foaming (egg white), and emulsifying (egg yolk). Ovalbumin is the most important protein in eggs, representing 60% of whole egg proteins, while ovotransferrin constitutes 13% and ovomucoid 11% of the egg white.[98] According to the USDA, the wholesale price of dried egg albumen protein was around $11/kg in March 2019.[99] The market price of egg protein is not that different from the market price of the milk proteins whey ($7/kg to $12/kg) and casein ($6/kg to $10/kg).[100] Our analysis indicates that the cost of PF protein should reach $10/kg between 2023-2025. The egg does not need to be replicated to be disrupted. Just like the milk market, **the modern food industry just needs to disrupt the egg protein ingredient market to push the primary egg production industry into a financial tailspin**.

Changes to price and demand for one particular type of meat in one industry will affect demand for meat in others,[101] so as cow meat begins to increase in price, other forms of meat may benefit from a temporary increase in demand. This is nothing more than a boom before the bust – ultimately, all animal-derived products will be disrupted, whether they come from a cow, pig, chicken, or fish. There are no species boundaries.

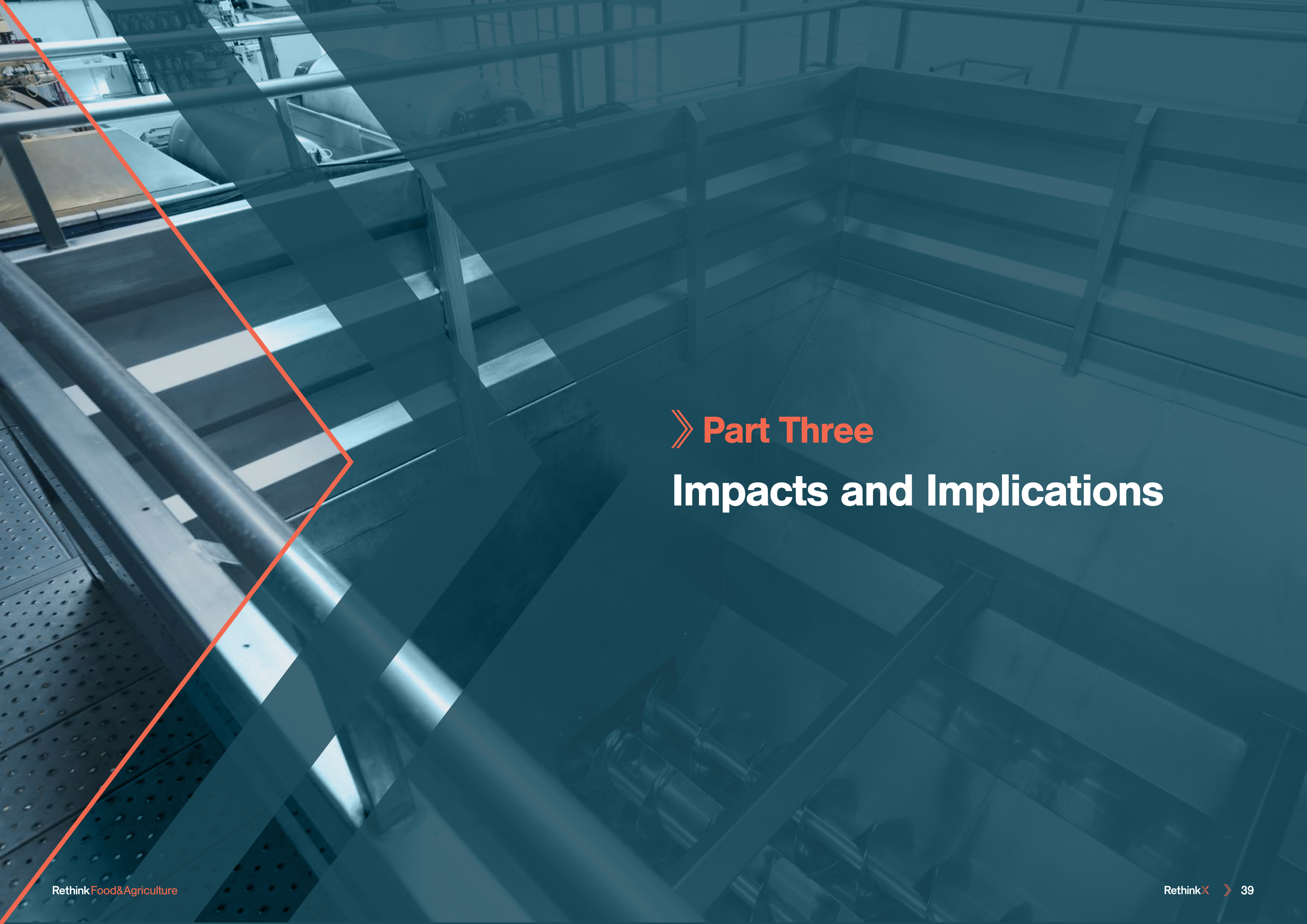
Ultimately, all industrial agriculture is volatile, low margin, and inefficient and will be bankrupted as a result of high cost of production and displaced demand.

We have focused in this report on the U.S. food and agriculture market, but our analysis of the disruption applies globally. The technologies underpinning the disruption can be developed, and are being developed, in China, Europe, Israel, and beyond – there are no geographical barriers to the roll out of modern food production.

*Clara Foods makes PF-based egg and egg white equivalents in the form of baking products, food and beverage ingredients, nutritional supplements and complete eggs*

*Source: Clara Foods; The Unreasonable Group*

**Ultimately, all industrial agriculture is volatile, low margin, and inefficient and will be bankrupted as a result of high cost of production and displaced demand**



## Part Three

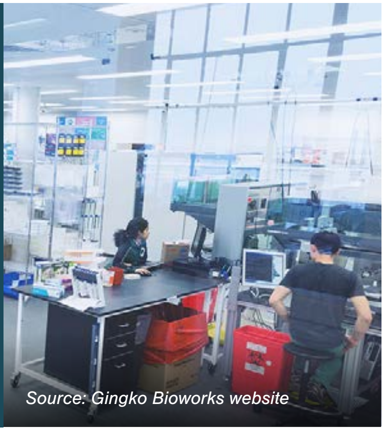
# Impacts and Implications

Every aspect of the value chain will be impacted to such a degree that, by 2030, the cattle industry in the U.S. will be all but bankrupt. Revenues of beef and dairy businesses will collapse, closely followed by those in the chicken, pig, and fish industries. Crop farmers will also suffer as feed production revenues slump. The knock-on effects throughout the supply chain will be dramatic. However, there will be enormous opportunities for businesses embracing modern food technologies to thrive.

The implications of the collapse of industrial livestock farming will ripple out far beyond food and agriculture. Livestock and its associated industries generate revenues of almost $1.25 trillion, or about 6% of U.S. GDP,[102] and have a deep impact on the world we live in. There are nearly one billion cows on the planet, 10% of which are in the U.S. They impact the environment profoundly through their use of water, land, feed, and waste in the form of greenhouse gases and manure. Indeed, in the U.S., cows generate 13 times more bodily waste than the entire American human population.[103]

**There will be enormous opportunities for businesses embracing new technologies to thrive**

*Companies designing microbes for protein production will dominate the food industry. Self-proclaimed 'organism company' Gingko Bioworks is working to build this future by designing custom micro-organisms to 'replace technology with biology' across multiple markets.*



*Source: Gingko Bioworks website*

Animal products are a major component of the American diet and so play an important role in health and well-being, while intensive animal farming is also a source of disease and antibiotic use. Animal agriculture is also a major employer – more than 1.2 million people work in the U.S. cattle industry alone – while the average American family spends $1,500 of its total annual income on animal products.[104,105]

Eliminating animals from the supply chain will, therefore, have profound implications, both direct and indirect, for the economy, human health, natural resource use, the environment, and society.

**Every aspect of the value chain will be impacted to such a degree that, by 2030, the cattle industry in the U.S. will be all but bankrupt**

## 3.1 Impact on the Food and Agriculture Industries

### Key Findings

» At current prices, revenues of the U.S. beef and dairy industries and their suppliers, which together exceed $400bn today, will decline by at least 50% by 2030, and by nearly 90% by 2035.

» All other livestock and commercial fisheries will follow a similar trajectory.

» At current prices, feed production revenues for cattle will fall by at least 50%, from $60bn in 2018 to less than $30bn in 2030.

» At current prices, revenues for fertilizers, pesticides, and seeds will also fall by 50% as fewer feed grain crops are needed to feed fewer dairy and beef cattle.

» The number of slaughterhouses and meat and dairy processors will drop by more than 50%.

» By 2035, 60% of the land currently used for livestock and feed production will be freed for other uses. This 485 million acres equates to 13 times the size of Iowa.

» Farmland values will collapse by 40%-80%. The outcome for individual regions and farms depends on alternative uses for the land, amenity value, and policy choices that are made.

The impact of the new food production system will affect different parts of the existing value chain in different ways. The impact on any part may be disproportionate to the number of livestock remaining.

# Box 12: Disproportional Impacts

The impact on various parts of the value chain are not proportionate. A 50% drop in the number of cows does not necessarily lead to a 50% reduction in revenues for inputs to the system or the value of assets. Each part of the value chain must be understood separately and the following rules guide our analysis:

Revenue = Price x Volume

## Stocks

Equipment, infrastructure, or land can suffer disproportionate impacts with revenues potentially declining to zero and profits and cash flows becoming negative.

**Volume:** Disproportionate impact. For example, if cropland use drops by 50% there would be a huge over-supply of tractors in the market, leading to a slump in used-tractor prices, which would reduce new tractor sales dramatically. The impact depends on the speed of disruption (relative to asset lifetime), as sales would level off at a proportionate reduction level once the over-supply has been cleared (in this instance, 50% below previous volumes).

**Price (or value):** Disproportionate impact. While volumes drop, new equipment prices can spiral upwards. This happens because lower sales volumes lead to diseconomies of scale and the impact of lower utilization of production facilities or infrastructure (with high operating leverage) can squeeze margins and lead to higher manufacturing costs (as fixed costs are spread over fewer units of demand). Furthermore, an oversupply of used equipment means prices drop. This affects residual values for new equipment bought on finance, leading to an increase in lease payments. Land and infrastructure that is no longer required can be stranded (any future value depends on alternative uses).

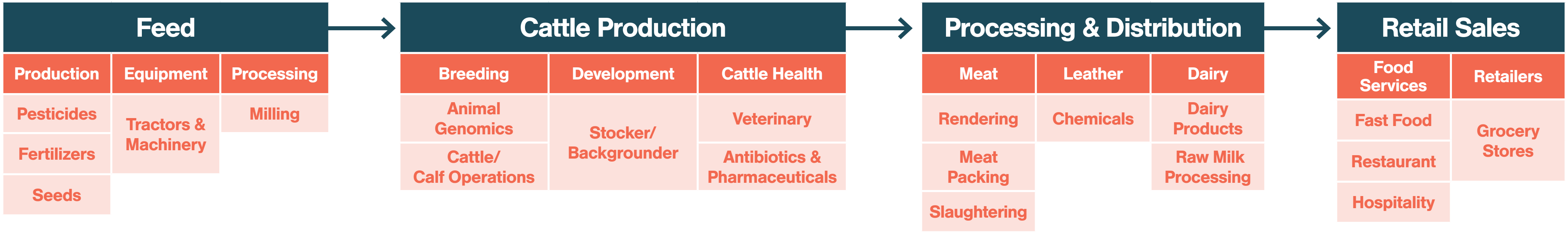
## Flows

Animal feed, fertilizer, or pesticides suffer proportionate impacts to volumes but disproportionate impacts to prices. This means revenues for these inputs can decline by more than the drop in the number of cows.

**Volume:** Proportionate impacts. Fifty percent fewer cows equals 50% less feed or antibiotics.

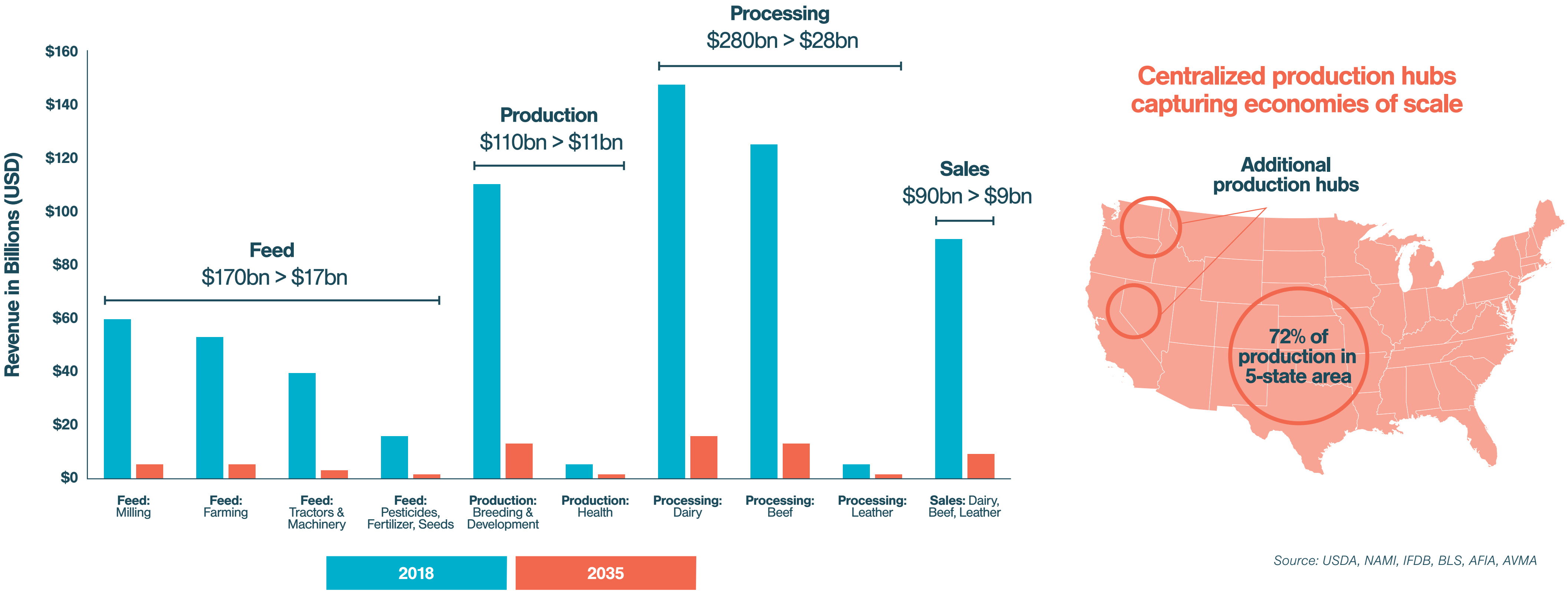
**Price:** Disproportionate impact. Commodities (in their raw form, such as corn) are expected to go down in price as supply exceeds demand and the marginal price is set by lower cost producers or even inventory liquidation. Inputs that require processing, however, can see price rises due to reversing economies of scale.[106]

## Figure 18. Today: Cattle Industry Supply Chain




*Source: RethinkX*

## Figure 19. Today: Cattle Industry Revenue and Structure




*Source: USDA, NAMI, IFDB, BLS, AFIA, AVMA*

## Impacts on the Current Supply Chain

### Livestock Farmers

In our forecast, the number of cattle will drop by 50% by 2030, with revenues directly associated with cattle production falling from $95bn to $50bn at current prices. By 2035, we anticipate that cattle production will drop by 75% from current levels, with revenues shrinking to $20bn. At current prices, revenues of the U.S. beef and dairy industries and their suppliers, which together exceed $400bn today, will decline by at least 50% by 2030, and by nearly 90% by 2035. All other livestock, aquaculture, and commercial fisheries will follow a similar trajectory. It is possible, however, that the disruption to these industries moves faster depending on factors such as policy and regulation.

> **Ultimately, the industrial processing industry will cease to exist in the large-scale facilities we have today and the 2030s will see the last industrial slaughterhouse in the U.S. close**

As a result, we anticipate that, by 2035, livestock farming will only operate in artisanal, high-cost, niche areas. Indeed, given the reversing economies of scale in industrial livestock farming as demand falls away, the cost advantages this industry enjoys over artisanal livestock farming will narrow or disappear. Given the inferred quality premium of artisanal producers over industrial producers, remaining meat and milk demand is likely to be met largely through artisanal production. Policymakers may also encourage a shift to artisanal production for health or environmental reasons, such as the superior carbon retention of soils, while industrial methods might see increasing taxes to pay for their waste byproducts and other negative health, resource, and environmental impacts.

### Meat Slaughterhouses and Processing Plants

The number of slaughterhouses and meat and dairy processors will drop by more than 50% by 2030 as the reduction in cattle leads to lower capacity utilization, leading to reversing economies of scale, closures, and consolidation.

The high capital needs and operating leverage of this industry will make it difficult to adapt to lower production volumes. We expect profitability to be heavily impacted early in the disruption. Businesses will either need to raise prices (further decreasing demand), consolidate, or go bankrupt. We expect the prospect of bankruptcy

will lead to consolidation first, leading to increased prices, followed by a wave of bankruptcies as the market crashes. Ultimately, the industrial processing industry will cease to exist in the large-scale facilities we have today and the 2030s will see the last industrial slaughterhouse in the U.S. close.

### Renderers

Renderers are the recyclers of the livestock industry. More than 90% of their raw materials are slaughter byproducts[107,108] while more than 60% of their output goes back to the industry as animal feed (40% for livestock and about 20% to pets),[109,110] so the wholesale disruption of livestock will have a significant impact on both supply and demand for their services. As the hundreds of non-meat products derived from the cow are produced through new technologies and far fewer cows are grown only for meat, the number of rendering facilities will fall by more than 50% by 2030 as renderers become increasingly obsolete.

### Arable Crop Farmers

Crop farming is closely entwined with animal agriculture, with just under half of U.S. cropland dedicated to feeding animals, both domestically and abroad.[111] While there are many varieties of crops used for livestock feed, the major staples for cattle are corn, soy, and hay. Together, U.S. beef and dairy cattle consume about 50% of the crops produced for U.S. livestock – 70% of the hay, 45% of the corn, and 17% of the soy.[112]

As a result, crops needed to feed cattle in the U.S. will fall by 50%, from 155 million tons in 2018 to 80 million tons in 2030.[113] As volumes drop, prices for these crops will also drop as supply exceeds demand and the marginal price is set by lower-cost producers. This means, at current prices, feed production revenues for cattle will fall by more than 50%, from $60bn in 2018 to less than $30bn in 2030. In addition, there will be a transformation in the crops required, away from large animal feed crops like soy and towards sugar and other biomatter that provide the optimal feedstock for PF. Due to the drastic increase in efficiency of new production methods, the volumes of crops required for food production will drop more than 10 times.[114]

With the massively-reduced amounts of feed and land needed to produce meat, crop farming will change drastically. There will be an increase in demand for alternative crops used either as feedstock for PF or as ingredients for the plant-based food sector. Eventually, however, PF producers will reduce costs by using recycled biomatter to feed their micro-organisms. In another virtuous cycle, this process may be enabled by enzymes produced via PF that can turn biomatter into usable sugars.

The bulk of arable crop production does not come from small family farms, but from large-scale farm corporations.[115] These companies are driven by profits derived by resource efficiencies (such as land, feed, and capital) and economies of scale. Once demand for conventional feed crops is surpassed by demand for other crops for modern foods, these companies are likely to switch production to higher-profit opportunities and scale down operations in shrinking markets.

Some arable crop farmers and landowners could adapt by moving to production of crops required by the modern system,[116] but the decline in volume of plant products required is such that few will succeed. Furthermore, as local indoor and vertical farming develop for the production of higher-value plant products, their choices will narrow further (we expect further disruptions to crop farming by indoor agriculture and vertical farming, but these are beyond the scope of this report).

The effects of a dramatic decrease in crop production will have ripple effects across the whole value chain, causing systemic disruption in pesticide, seed, and fertilizer companies, as well as in other inputs for crop farmers, such as electricity and fuel.

Volumes of fertilizers, pesticides, and seeds will fall by 50% by 2030, meaning, at current prices, pesticide revenues will fall to $1.5bn, fertilizer revenues to $1.5bn, and seed revenues to $750m. Meanwhile, revenues for animal health will also be cut by more than half from current levels of almost $4bn ($1.2bn is spent on antibiotics and other pharmaceuticals and $2.8bn on other veterinary services).

### Tractor and Equipment Manufacturers

The market for tractor and agricultural machinery in the U.S., revenues for which are about $40bn, will shrink dramatically.[117,118] In 2007, there were an estimated 4.4 million tractors and 350,000 combine harvesters in use in the U.S.[119] As the amount of land required for crop production decreases dramatically, so too will the need for new farm equipment. Equipment will be left stranded as the used market is flooded with cheap, used units that will largely replace new equipment sales, at least until the oversupply is cleared. As used equipment prices drop, equipment lease payments will rise (due to decreased residual values), making new equipment less attractive. Furthermore, declining economies of scale in equipment production will lead to lower margins, which will have to be offset by increasing prices, triggering a vicious cycle for equipment manufacturers. In the 1980s farm crisis, a similar phenomenon of oversupply (due to falling profits) took place. Sales of combines and tractors (80% of the market) both dropped by about 70% from 1979 to 1984. This caused mass temporary and permanent shutdowns of manufacturing facilities, layoffs, and company mergers. We are likely to see similar industry turmoil within the next decade.

**The volumes of crops required for livestock production will drop by more than 10 times**

## Opportunities in the New Supply Chain: Who Will the Winners Be?

### Figure 20. Future (2030-): PF Industry Supply Chain

**Feed**
- Crops
- Biomatter

→

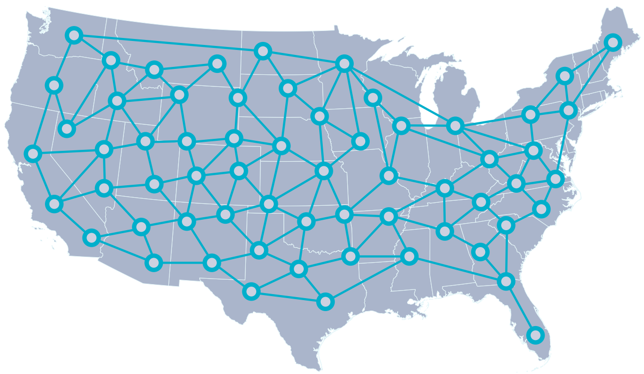
**Fermentation Farms**

| Food | Pharma | Materials | Cosmetics |
|---|---|---|---|
| Branding | | | |
| Packaging | | | |
| Distribution | | | |

→

**Retail Sales**

| Platforms | Point of Sales |
|---|---|
| Online/ TaaS Delivery | Restaurants |
| | Fast/Casual |
| Cloud Kitchens | Hospitality |
| | Supermarket |
| | Grocery |



**Decentralized production hubs to capture network effects**

**Food-as-Software Stack**

| Food Dev/App Layer | Core IT Layer | Fermentation Tech Layer |
|---|---|---|
| Molecular Cookbook/ Systems Integration | AI Analytics | Tanks & Equipment |
| | Simulations & Testing Software | Control Systems |
| | Cloud Computing | Systems Integration |
| | Operating Systems | |
| | Databases | |
| | Communications | |

Foundation

| Precision Biology Layer |
|---|
| Molecule Design & Development |
| Organism Design & Development |
| **Precision Biology Core** |
| Gene Sequencing |
| Gene Synthesis |
| Molecular Databases |
| Computational Biology |
| Foundries |

*Source: RethinkX*

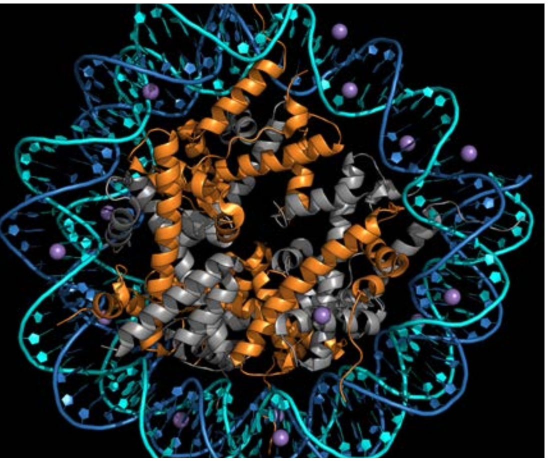
**The winners in food production are likely to be biotechnology and software companies – those that have a model where efficient product distribution is key – or those retailers and distributors able to adapt to and help shape the new supply chain**

The disruption of the cow by modern foods will trigger a transformation of the whole supply chain, with different industries seeing disproportionate losses and gains. Picking individual winners is likely to be much harder than identifying losers, but the opportunities will be enormous.

The successful food and agricultural businesses of today may not be the ultimate winners. Incumbent businesses are often handicapped by incentives, mindsets, and organizational structures and processes that favor incremental improvement over disruptive innovation. As the markets they operate in are disrupted, they have the potential to adapt, but that is no guarantee they will.

Modern production technologies will blur the boundaries between food, materials, healthcare, and cosmetics, providing an enormous opportunity for those companies, regions, and countries taking a lead. Protein producers will not have to restrict themselves to one particular industry as many proteins can be used for many applications. For example, collagen is an input in a range of end markets including leather, cosmetics, and food.

As the costs of modern meat and milk products drop below those of animal-derived competitors, new producers may flourish as their margins increase far beyond those in livestock farming. For early in the disruption, animal products will set the marginal price for modern foods. Given the cost advantages modern products enjoy, this will lead to a period of exceptional margins that is likely to drive even greater investment in the modern food sector. However, over time, as supply grows and competition increases, modern products themselves will begin to set the marginal price, thus reducing margins back to a longer-term, equilibrium level.



The winners in food production are likely to be biotechnology and software companies – those that have a model where efficient product distribution is key – or those retailers and distributors able to adapt to and help shape the new supply chain.

## Biotechnology and Software

Huge opportunities will emerge in many areas of biotechnology and software, including product simulation and testing, artificial intelligence, molecular databases, and gene sequencing and editing. The profitability of these technologies depends on the system that emerges – an open-source system of development and production is likely to out-compete a system that privatizes parts of this platform, like the pharmaceuticals industry does today.

We are already seeing mainstream pharma companies showing interest in this space, with Merck identifying “clean meat” as one of its innovation fields in 2018,[120] but we also see moves for an open-source system – crowd-sourced synthetic biology (“bio-hacking”), for example, is becoming more and more popular.[121]

Ultimately, decisions made regarding intellectual property (IP) rights and approval processes will determine which system develops (see Part 4).

## Fermentation Farms

Fermentation farms will be the new food farms. There will be opportunities involved in engineering, designing, building, and operating them. Industries with experience operating fermentation tanks, which include pharmaceutical manufacturing, food and drink, and bioethanol companies, have a head start.

These tanks are likely to be owned in a variety of ways. Current food producers or retailers may own and operate their own production, or we may see independent fermentation farm companies that either license or supply to a range of customers.

## Food Distribution

Food and drink companies that operate with a significant distribution infrastructure are more likely to succeed. For example, beer and soda companies like Pepsi, Coca Cola, and Heineken specialize in distributed, local production and are experienced in branding, packaging, and distribution, often with a licensing model. Meanwhile, internet-based distributors like Amazon have already started to move into the food market – Amazon bought Whole Foods in 2017 and was the fifth largest grocery business by sales in America in 2018.[122]

As food production becomes decentralized and moves into urban centers, production, distribution, and even retail will begin to merge. Grocery stores might have meat fermentation tanks on-site – just like many brew coffee and bake bread and cakes instore today. Pizza stores will be able to make fresh cheese onsite with their own proprietary blend of molecular taste, aroma, texture, and nutritional attributes (for example, more protein than a steak, 'good' fats only, and no sugar).

### Food Delivery

Food will be much cheaper following the disruption. When these savings are combined with those from the transport-as-a-service (TaaS) revolution, where car owners give up their vehicles in favor of an autonomous, electric, ride-hailing service (see our Rethinking Transportation report), food delivery will be so cheap and convenient that many consumers will question the need to buy food to prepare at home. The convergence of TaaS with emerging technologies such as autonomous delivery robots and drones will enable new product and business model innovation that will further disrupt not just transportation and logistics, but also the food industry itself. For example, FedEx has announced a delivery robot and a partnership with Pizza Hut (joining Amazon and Ford), while Alphabet's Wing Aviation got approval from the Federal Aviation Administration to run a drone delivery system in the U.S.[123,124]

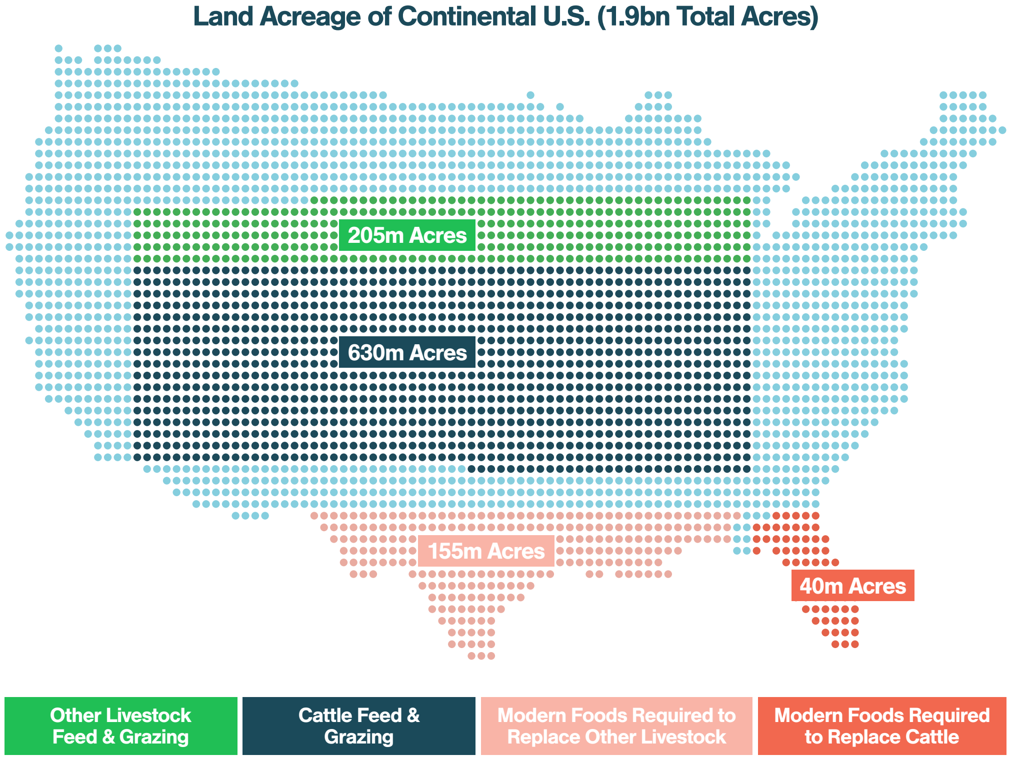

*Source: Starship Technologies*

In this competitive market, brands will continue to be important. New brands, many of which will be local – reflecting the decentralized nature of food production – will appear, while existing brands will be forced to reposition themselves to remain relevant. For example, Tyson Foods, the world's second largest processor of beef, pork, and chicken, is already calling itself a protein company.[125,126]

# 3.2 Impacts on Land Use and Value

The implications of the disruption for land use will be profound. Today, more than 835 million acres – equivalent to 40% of the total U.S. land mass – is used to feed livestock (630 million is used for beef and dairy cattle). Of this, 655 million acres are used for grazing and 180 million to grow feed crops such as soy, corn, and hay.[127]

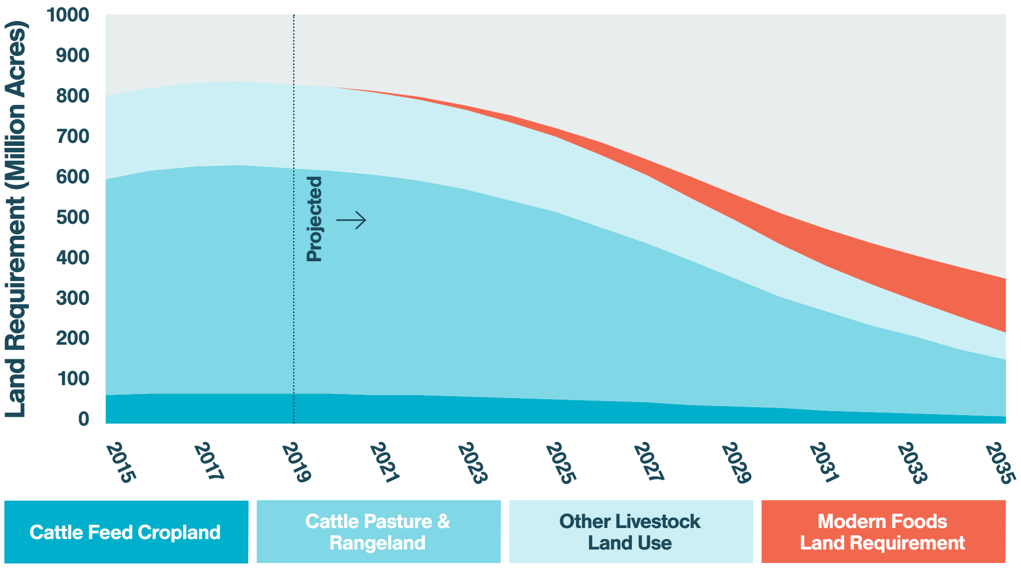
### Figure 21. Land Required for Modern Foods to Disrupt 100% of Animal Agriculture




*Source: RethinkX*

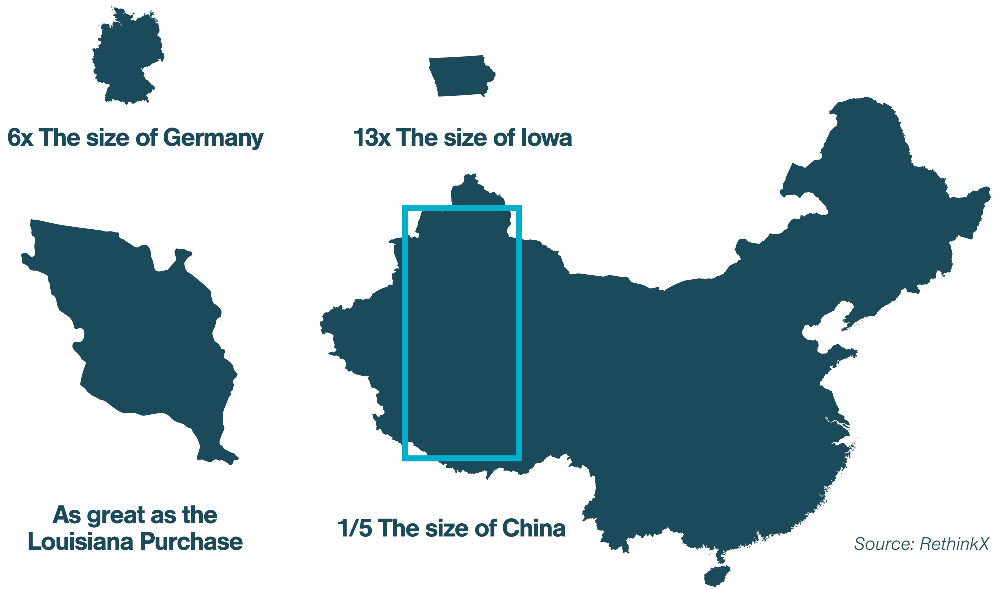
**About 95% less land required for protein production from PF than from cattle**

## **Figure 22.** Estimated Change in U.S. Land Requirements Over Time




*Source: RethinkX*

## **Figure 23.** What is 485 Million Acres Equivalent To?




*Source: RethinkX*

By contrast, the far greater efficiency of PF technology means that its products typically require less than one tenth of the cropland of their animal-derived alternatives. In the case of cattle, current research suggests that a PF-enhanced burger will use 94% less land than equivalent beef or dairy products.[128]

As a result, by 2030, cattle pasture, rangeland, and feed cropland will decline by about 50%. This means the disruption of the U.S. beef and dairy industries by modern production methods will free up about 300 million acres of land by 2030, rising to 450 million acres by 2035.

Taking all livestock into account and including land needed for modern production, 325 million acres will be freed up by 2030, and up to 485 million acres by the 2035. This is 13 times the size of Iowa, or six times the size of Germany. Excluding land for modern production, 620 million acres will be freed up by 2035, more than the 530 million acres acquired during the Louisiana Purchase of 1803.[129]

The opportunity to reimagine the American landscape by repurposing this vast expanse of freed land is wholly unprecedented. A number of land use options are available, including urban and suburban development and conservation. A substantial portion could, for example, be used to restore wildlife habitat, safeguard biodiversity, improve water quality, and combat climate change through reforestation (see section 3.4).[130]

### Impact on Land Value

Land values will be disproportionally affected by the disruption of livestock farming. Overall, we will see a rapid collapse in value, but the outcome for any particular area or farm is more nuanced. Some land will still be needed to provide inputs for the modern food system, or for the legacy livestock market.

The value of productive farmland depends on land scarcity, cost of capital, and crop prices.[131] If land no longer has a productive agricultural use, its future value will depend on its alternative uses. These could include amenities (ranches, national parks, wilderness), solar farms, commercial and industrial development, housing, forestry, and carbon sinks (reforestation or regenerative agriculture).

**Productive Land:** Even land that is still put to productive agricultural use might fall in value in the medium term due to an oversupply of land and falling crop prices (see section 3.1 on arable crop farmers). We estimate the decline in the value of land that still has productive agricultural use at 40%. Two major farm crises during the 20th century provide some context for this figure. Farmland value dropped dramatically – by more than 50% (from $69/acre to $30-$33/acre) – during the 1920s and 30s[132] following sharp falls in crop prices[133] and again during the late 1980s, this time by 40%, as a result of both low crop prices and high interest rates.[134]

**Land Freed from Agriculture:** The majority of cropland and pastureland is far from cities with no prospect for productive agricultural use and little amenity value. It is likely, therefore, to plummet in value. Pastureland in the U.S. has an average value of $1,350 per acre, while cropland is valued at $4,090,[135] although these averages hide a wide spread. The best proxy for land that has no alternative productive use might be ranch land, which has an average value in Montana of $600 an acre. However, prices might collapse well below this number as a huge oversupply of land hits the market. We estimate land that has no future economic use will decline in value by at least 50% and, in some instances, by more than 80% (depending on its current value and future amenity value).

Conversely, land that is near to cities might see values increase if planning policies allow development for residential or commercial use.[136]

### Banking and Finance Implications.

Farm debt has increased to more than $400bn, reaching levels (in real terms) not seen since the 1980s farm crisis.[137] Farmers use land as collateral to purchase equipment and cover operating costs such as seeds, fertilizer, and energy. As the value of animal products, feedstocks, and farm land collapses and farms struggle to cover their operating and capital costs, banks will stop accepting land as collateral and will stop lending fresh capital to keep farms operating. As credit markets freeze, more and more crop farmers will not be able to pay back loans. Banks that specialize in agricultural finance may themselves get frozen out of credit markets. We believe that, with proper planning, the risk of contagion would be smaller than during the 1980s and 2008 banking crises.

## 3.3 Impact on Associated Economic Sectors

The agriculture sector is entwined with the broader economy, so changes to the agricultural system will have implications for other sectors, just as changes in other sectors will impact agriculture. Furthermore, modern technologies will be used in other sectors, so improvements in production methods, costs, and capabilities there will accelerate development of the underlying technologies and other inputs into the food system.

**Materials:** As the ability to produce bespoke molecules and structures improves, entirely new materials not provided by nature (that cannot be produced via synthesis) become possible.[138] The market opportunity for these technologies is enormous and includes clothes, furnishings, and organic and construction materials.

**Transportation:** The modern food system will be far more localized, with shorter supply chains and local procurement, thus reducing the need for transportation. There will be a dramatic reduction in the shipping not just of livestock,[139] animal feed, pesticides, fertilizers, and other inputs, but of the end products as well. In fact, of the four trillion ton-miles of goods shipped in the U.S., at least 12% can be attributed to livestock.[140]

**Energy:** There will be an increase in the amount of electricity used in the new food system as the production facilities that underpin it rely on electricity to operate. This will, however, be offset by reductions in energy use elsewhere along the value chain. For example, since modern meat and dairy products will be produced in a sterile environment where the risk of contamination by pathogens is low, the need for refrigeration in storage and retail will decrease significantly.[141,142]

Reductions in energy consumption in the value chain will also hit demand for oil. The oil industry is connected to agriculture in many ways – to power mechanized equipment in farming, to provide the petrochemicals used in fertilizers, pesticides, synthesized food products, and plastics in packaging, and to make the diesel used in transportation and refrigeration. In fact, the on-farm fuel requirements (diesel) make up 24% of agricultural energy consumption at 74 million barrels of oil equivalent (BOE) a year.[143] U.S. agriculture as a whole is responsible for about 2% of oil products consumption, which is equivalent to about 150 million BOE per year.[144]

By 2030, we expect that at least half of this demand will disappear as all parts of the supply chain related to growing and transporting cattle are disrupted.

**Healthcare:** Modern food products should lead to a reduction in diet-related health issues, such as obesity, diabetes, cancer, and heart conditions (see health implications below).

**Microbrewing takes on a new meaning**

Anywhere beer is made today, it will soon be possible to make protein.

# 3.4 Wider Environmental, Social, and Economic Implications

## Key Findings

### Environmental Implications:

- Direct U.S. greenhouse gas (GHG) emissions from cattle will drop by 60% by 2030, on course to almost 80% by 2035.
- When the modern food production that replaces animal agriculture is factored in, net emissions from the sector as a whole will decline by 45% by 2030, on course to 65% by 2035.
- Water consumption in cattle production and associated feed cropland irrigation will fall by 50% by 2030, on course to 75% by 2035.
- When the modern food production that replaces animal agriculture is factored in, net water consumption in the sector as a whole will decline by 35% by 2030, on course to 60% by 2035.

### Health Implications:

- Nutrition will improve for everyone. In the developing world in particular, access to cheap protein will have a hugely positive impact on hunger, nutrition, and general health.
- Rates of foodborne and human-animal crossover illnesses will decrease significantly, as will antibiotic resistance in disease-causing bacteria.

### Social Implications:

- Higher quality food will become cheaper and more accessible for everyone.
- The poorest American families could save 8% of their income each year, equivalent to $700, by 2030 through cost savings made by buying modern foods that are up to 80% cheaper than existing animal-derived products.
- Half of the 1.2 million jobs in U.S. beef and dairy production and their associated industries will be lost by 2030, climbing towards 90% by 2035.
- Employment and incomes in all other U.S. livestock and commercial fisheries industries will follow suit, for a total loss of more than 1.7 million jobs by 2035.
- The emerging U.S. PF industry will create at least 700,000 jobs by 2030 and up to 1 million jobs by 2035.

### Economic Implications:

- The cost of modern foods and other PF products will be at least 50% and as much as 80% lower than the animal-derived products they replace, which will translate into substantially lower prices and increased disposable incomes.
- The average U.S. family will save more than $1,200 a year in food costs. This will keep an additional $100bn a year in Americans' pockets by 2030.

### Geopolitical Implications:

- Trade relations will shift because decentralized food production will be far less constrained by geographic and climatic conditions than traditional livestock and agriculture.

» Major exporters of animal products, like the U.S., Brazil, and the European Union, will lose geopolitical leverage over countries that are currently dependent upon imports of these products. Countries where exports of animal products or feed make up a large proportion of GDP will face challenges if they fail to transition to new industries.

» Countries importing animal products will benefit as they can more easily produce these products domestically at a lower cost using modern production methods.

» Large endowments of arable land and other natural resources are not required to lead the disruption, so the opportunity exists for any country to capture value associated with a global industry worth hundreds of billions of dollars that ultimately emerges over the course of this disruption.

## 3.4.1 Environmental Implications

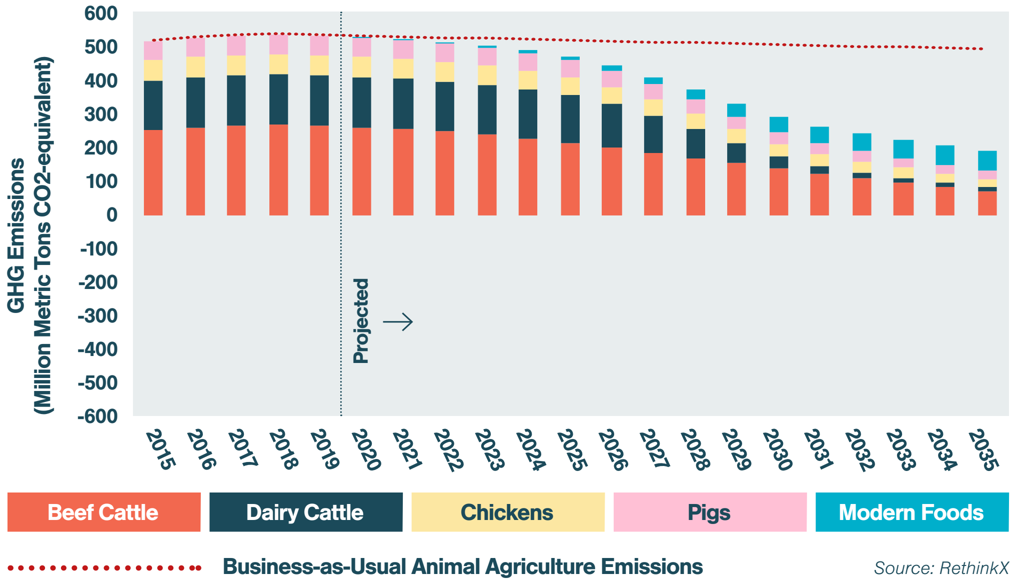
Industrial animal agriculture is a major contributor to many pressing environmental problems, including climate change, deforestation, soil erosion and degradation, water pollution, local air pollution, habitat and biodiversity loss, and stratospheric ozone depletion. Because of the enormous ecological footprint of livestock on the landscape, not just in the U.S. but worldwide, the modern food disruption presents the greatest opportunity for environmental restoration in human history.

### Climate Change

Animal agriculture is responsible for about 8% of U.S. GHG emissions.[145,146] Beef and dairy cattle are by far the largest source in the sector, emitting GHGs both directly via methane from enteric fermentation and manure, as well as indirectly via land use change, feed production, and the energy and transportation use associated with production and distribution. Although estimates vary, FAO data indicate cattle alone account for 78% of total U.S. emissions from animal agriculture.[147]

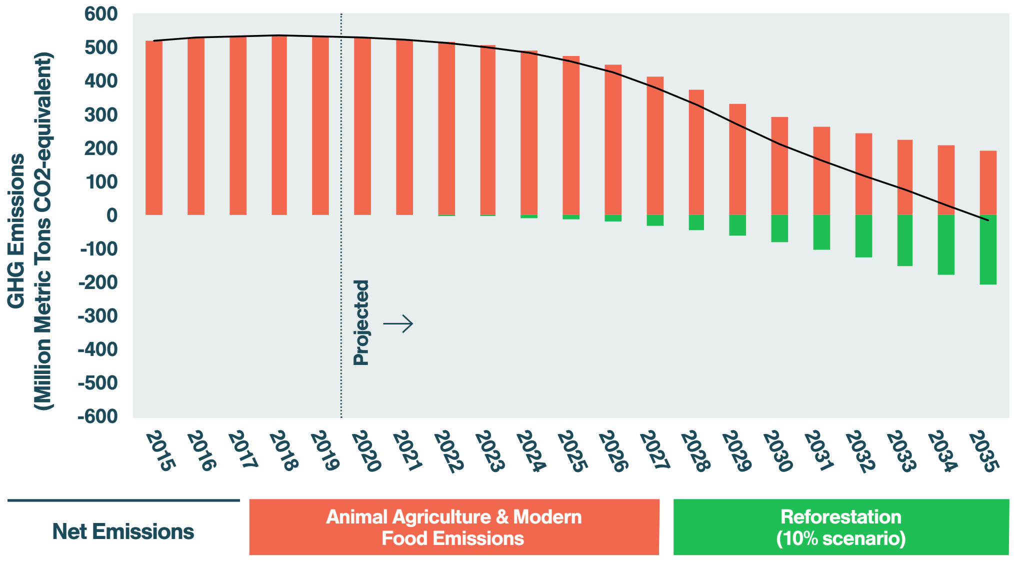
We estimate that the modern foods disruption will reduce direct U.S. GHG emissions from cattle by 60% by 2030, on course to almost 80% by 2035. Likewise, we estimate that direct emissions from all animal agriculture combined will fall by 55% by 2030, on course to 75% by 2035. When the much smaller carbon footprint of modern food production that replaces animal agriculture is then factored in, we project that net emissions from the sector as a whole will decline by 45% by 2030, on course to 65% by 2035.

**Figure 24. Greenhouse Gas Emissions from Animal Agriculture**




*Source: RethinkX*

**Figure 25. Net Greenhouse Gas Emissions – 10% Reforestation Scenario**




*Source: RethinkX*

The land freed up by the disruption presents enormous opportunities. If conservation with reforestation is prioritized, the potential arises not only to mitigate ongoing environmental impacts but also to actively aid recovery of the atmosphere, local water and air quality, soils, natural habitat, and biodiversity. For example, even without dedicated efforts to maximize carbon sequestration, actively reforesting 10% of the 485 million acres of land freed up by the modern food disruption would allow us to capture more than 200 million tons of CO2e each year, making what remains of the animal-agriculture sector carbon neutral by 2035 (Figure 25). If 100% of the freed land were dedicated to reforestation and efforts were made to actively utilize tree species and planting techniques that maximize carbon sequestration, we could capture more than 5.5 billion tons of CO2e each year by 2035. This would be enough to fully offset all sources of U.S. GHG emissions combined, even at their current levels – in reality total emissions will fall substantially between now and 2035 because of disruptions in energy and transportation.

## Water

Water scarcity is a serious environmental problem in the U.S., as it is elsewhere across the world.[148] California, for example, experienced continuous and record drought for 376 consecutive weeks from December 2011 until March 2019.[149] Research suggests that the problem is going to get worse, with changes in precipitation patterns caused by climate change and the depletion of groundwater combining to create serious water shortages in the coming decades.[150]

Agriculture is responsible for almost 90% of all freshwater consumed in the U.S.[151] The majority of that consumption is for crop irrigation, but the livestock industry also consumes water directly as drinking water, for sanitation and processing, and to support aquaculture. All told, U.S. livestock production and its associated feed croplands account for one third of all freshwater consumed in the country.[152]

Food production via modern production methods will still require freshwater, but in much smaller quantities. Recent research has found that PF products use 87% less water than conventional cattle-derived products, largely because of the reduction in irrigated crops necessary per unit of output. Not including this modern production, water consumption in animal agriculture will decline in direct proportion to the sector's collapse, such that water use in the beef and dairy industries will fall by 50% by 2030 and by 75% by 2035. The disruption of all other livestock will follow shortly after cattle, such that water use for U.S. animal agriculture as a whole will decline 45% by 2030 and 70% by 2035. When the water use of modern food production that replaces animal agriculture is included, we project that net water use for the sector will fall by 35% by 2030, on course to 60% by 2035.

## Waste

**Manure:** Industrial livestock operations produce hundreds of millions of tons of manure every year, which contribute to a number of environmental and human health impacts.[153] Altogether, the largest concentrated animal feeding operations (CAFOs) produce around 370 million tons of manure a year.[154] Leaking and overflowing manure lagoons and the over-application of manure as fertilizer cause eutrophication (overly-enriched water) in nearby aquatic habitats, which leads to toxic algal blooms, anoxic conditions (a total depletion of oxygen in water), fish kills, and habitat destruction. Fecal bacteria accumulate in both surface and groundwater, contaminating water that may be used for drinking or irrigation.[155] Particulate matter from spraying manure on agricultural fields is also a significant health concern and nuisance to people living near farms.

By contrast, there is no manure created by modern food production because there are no animals involved in the process. One early study estimates that a product made using PF generates 92% fewer pollutants than a comparable animal product.[156]

The exact composition of waste products varies greatly among fermentation processes, but typically includes spent microbial biomass and wastewater.[157] If the microbes are not part of the end product, they are disposed of or used in other ways, such as fertilizing or enriching the soil. Most of the waste from the facility will be wastewater that can initially be treated onsite before being released into municipal waterways. Studies have shown that certain kinds of fermentation waste can be used to remediate waterways, and there is no risk of gene transfer from inert GM to natural microbes.[158]

**Endocrine Disruptors:** These are substances that either act as hormones themselves or modify normal hormonal function. The use of hormones to promote growth of cattle is approved in the U.S. by the FDA. Growth hormones include estrogen, progesterone, testosterone, and their synthetic versions.[159] Their use has increased the average weight of a beef cow by 18kg-25kg per head, thereby reducing costs by up to 7%.[160,161] These hormones enter the environment in significant quantities through animal waste, where they act as endocrine disruptors. Chronic exposure to them has been linked to an increased incidence of cancers, sexual disorders, and altered sex ratios in humans, as well as reproductive problems in aquatic wildlife.[162] This is why the use of hormones in beef is banned by the EU, as is the sale of imported beef that has been grown using steroid hormones.[163]

Most methods of production using modern food ingredients also use growth hormones in the production of cells, but the hormones are unlikely to be present in the final product in concentrations higher than conventional products. Crucially, unlike animal waste, the outputs of modern foods can be far better contained throughout the production process to avoid release into the environment.

### Deforestation and Biodiversity Loss

Almost a fifth of the Amazon rainforest has been lost since 1970, more than 80% of which is the result of clearing land for cattle ranching.[164] Worldwide, nearly 20 million acres of forest are cleared each year,[165] the equivalent of the landmass of South Carolina.

Forests deliver a wide array of ecosystem services and are vitally important to the health of the planet. They provide oxygen and sequester carbon dioxide, regulate water and nutrient cycles, provide habitat for species (including many that are threatened, endangered, or critically endangered), support biodiversity, purify the air, water and soil, prevent soil erosion, and provide essential resources for human consumption, including pharmaceuticals. They are also an essential source of livelihoods for indigenous populations across the world.[166] Large swathes of other natural environments are also converted for agriculture, such as wetlands, prairies, and savannah. Across the Americas, 95% of high-grass prairies have been transformed into farms.[167] This natural habitat destruction has contributed to species extinction hundreds of times faster than the natural background rate, threatening vital ecosystem services across the world. Indeed, agriculture is the single biggest driver of biodiversity loss in the world today.[168]

Modern food production will obviate the need not just for grazing and feed cropland, but for palm oil plantations, which are another major cause of deforestation.[169] Palm oil can already be produced via PF at a lower cost than tree-produced palm oil and, as PF costs continue to fall, we expect a rapid displacement of this market.[170]

Modern foods, therefore, have the potential to greatly reduce, if not entirely eliminate, several key underlying causes of deforestation, habitat fragmentation and destruction, and the loss of biodiversity associated with them.

## 3.4.2 Health Implications

### Disease

Each year in the U.S., 48 million people get sick from contaminated food.[171] Livestock are vehicles for foodborne illness when bacteria such as Salmonella, Campylobacter, E. coli, and Listeria are present in the intestines and feces of animals and infiltrate the food chain during slaughter, processing, distribution, and waste disposal. Any food product that comes into contact with these bacteria can be affected, from vegetables irrigated with contaminated water to cross contamination via kitchen surfaces. Every year, 42% of outbreak-associated illnesses can be attributed to animal products – 14% from dairy and 7% from beef.[172] These bacteria, and even some infectious diseases (zoonoses), can also be passed through direct human to animal contact – slaughterhouse workers are one of the groups monitored to assess this.

Modern food production means eliminating animals and their fecal matter, which will drastically limit food contamination and disease transmission while ensuring that food has a longer shelf life. Rates of foodborne and human-animal crossover illnesses will, therefore, decrease significantly.

The risk of antibiotic resistance in disease-causing bacteria will also be reduced. About 80% of global antibiotic use is for livestock.[173] The use of antibiotics is imperative to maintain the success of industrial animal agriculture due to the increased risk of disease due to confinement and crowding. Antibiotics are also used to promote growth, although in many countries, including the U.S., measures are being implemented to prevent or at least reduce this practice[174] – in 2017, the FDA banned the use of medically-important antibiotics for growth promotion, effectively reducing usage by 30%

from the previous year.[175] Cattle consume more antibiotics than any other livestock species in the U.S., many of which are medically important to humans.

Despite progress, antibiotic-resistant bacteria, or superbugs, are becoming more prevalent in society, presenting one of the most pressing hazards to human health. An estimated 10 million lives will be lost every year by 2050, along with a total $100 trillion of economic output, if no action is taken.[176]

The disruption of intensive livestock farming by modern food production will significantly reduce the use of antibiotics as well as growth-promoting and therapeutic drugs, especially in countries with no restrictions. This will slow down the trajectory of antibiotic resistance, giving the pharmaceutical industry more time to discover and develop new medicines.

Antibiotics may still be required in PF production to prevent contamination by 'bad bacteria', but these antibiotics would not be present in the final product, instead making up a component of the waste. This would be subjected to wastewater treatment, where they would be completely removed before the treated water is released into the wider environment.

### Nutrition

Nutrition is often an underlying factor in many health conditions, including diabetes, cancer, obesity, and heart disease. Not only do people suffer greatly from these conditions, but they impose huge costs on society. For example, the cost of chronic disease due to obesity in the U.S. alone is estimated to be about $1.7 trillion every year in direct and indirect costs.[177] This is 36% more than the total revenues of the livestock industry in America.

Because modern food production allows for the customization of proteins, molecules and, therefore, end products, it represents an opportunity for producers to maximize beneficial nutrients and minimize harmful substances. Diets could, therefore, not only be dramatically improved but tailored to individual requirements without the need for behavioral change – people could still eat as many hamburgers as they want without the side effects. By improving access to a more balanced and nutritious diet, modern production methods will, therefore, bring better nutrition to more people. In the developing world, especially parts where protein deficiency and/or malnutrition is a problem, access to a consistent source of inexpensive protein will have a hugely positive impact on hunger, nutrition, and health, as well as knock-on effects for population growth and even IQ.[178] On the other hand, potential health issues could arise when incorporating novel food components into the food chain.

## 3.4.3 Social and Economic Implications

### Food Quality and Prices

Higher quality, healthier food will become cheaper and more accessible for everyone. Over time, Americans have progressively spent a smaller portion of their income on food, moving from 43% in 1901 to 13% in 2017.[179] In real terms, this is almost $8,000 a year in 2017, a significant amount for the average family. Of this, $1,500 a year is spent on meat, dairy, fish, and eggs. While animal-derived foods are already relatively inexpensive compared with other foods (thanks largely to subsidies), modern production methods will bring the cost of these foods down so that the average U.S. family will save $1,200 a year on food. This will keep an additional $100bn a year in Americans' pockets by 2030. For the poorest families, this will be significant. The poorest 20% of U.S. households spent 35% of their income on food in 2017, of which 30% (10% of total income) was directly on animal-derived products. Assuming an 80% drop in the cost of animal products, the poorest American families could save 8% of their income each year, equivalent to $700, by 2030. These amounts does not include the taxpayer money saved because of reduced government subsidies to the livestock and crop farming industry or current expenditures in healthcare to treat livestock food-related diseases.

We also expect that food quality for everyone will improve. In the short term, we may see a 'quality rebound', where the total consumer spend on food falls by less than the cost decreases, simply because superior food products are consumed. In the long term, prices will trend to cost even as quality, taste, and convenience improve.

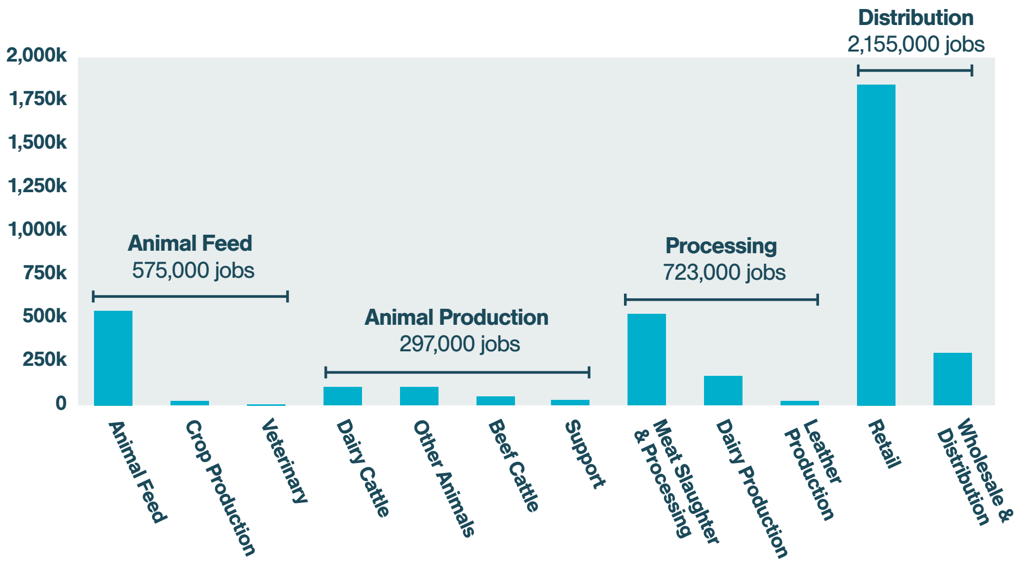
### Jobs

In the U.S., there are currently almost 2 million people employed by the livestock sector (excluding distribution), 1.2 million of which work in the cattle industry (see Figure 26), and millions more globally.[180] Not all these are at risk, but any jobs related to raising, slaughtering, and processing animals and animal products are likely to be lost during the modern food disruption.[181] By 2030, we estimate that about 600,000 jobs directly related to cattle production will be lost. By 2035, this number will rise to about one million. Across the entire livestock and fisheries industries, more than 1.7 million jobs could be lost.

The full impact of these job losses may be cushioned by the fact that many farmers already require additional household income to support themselves. In fact, nearly 80% of beef cattle operations make less than 25% of their income from farming, with 36% of operators holding a job outside the farm.[182,183]

Modern production, however, has seen and will continue to see job creation for fermentation farmers, bioengineers, protein engineers, metabolic engineers, cell biologists, computer scientists, IT workers, food scientists and designers, nutritionists, and other similar professions. Many of the jobs in the new industry will be highly skilled and specialized. There will also be demand for manufacturing jobs to create the capital equipment for fermentation farms, and for jobs on the farms themselves. This should see the creation of about 700,000 jobs. For example, Beyond Meat, which produces plant-based meat and has been in stores since 2014, has successfully scaled up production, opening a new factory in 2018 in Columbia, Missouri, bringing more than 250 new jobs to the area.[184] In the UK, plant-based food producer Vbites will repurpose an old Walkers Crisps factory in 2019, bringing 300 new jobs.[185]

## Figure 26. Employment Across the Livestock Value Chain




*Sources: BLS, AFIA, AVMA*

## Box 13: Jobs in Numbers

Labor requirements in the emerging modern foods industry are still highly uncertain at this early stage of disruption but, with cautious assumptions, we can make some useful inferences based on the examples of two current market leaders in plant-based meat – Impossible Foods and Beyond Meat.

Detailed production data are not available, but we estimate that each company currently employs about 400 people and is producing approximately 2.5 million 4-ounce servings a month.[186,187] This amounts to 300,000 4-ounce servings of plant-based meat per employee per year. As a point of comparison, these output figures closely match those of the existing brewing industry in the U.S. – domestic beer production employs 212,000 people supporting 64 billion 12-ounce servings in annual beer output for an average of 303,000 servings of beer per year per employee.[188]

We forecast that the modern food disruption of cattle alone will result in combined annual output of nearly 10 billion kilograms (105 billion servings) of plant-based and cell-based meat and dairy products by 2030. The disruption of all other animal agriculture and fisheries will require an additional 10 billion kilograms, for a total of 20 billion kilograms or 210 billion servings each year. At the current production rate of 300,000 servings per year per employee, we therefore expect the half of the modern food industry that disrupts cattle to employ about 350,000 people in manufacturing and distribution by 2030, and the other half that disrupts all other animal protein markets (chicken, pork, and fish) to employ another 350,000, for a total of approximately 700,000 jobs.

The size of the modern foods industry will then more than double over the course of the 2030s. Moreover, new applications of the technology in medicine, textiles, building materials, and other sectors will expand the industry's market. At the same time, however, the job requirements on a per-unit-output basis will decline as the industry matures and the initial build-out phase ends. With other exogenous factors such as advances in automation to consider, the long-term job requirements of the industry beyond 2030 are highly uncertain and, therefore, difficult to predict.

Lastly, the land freed from animal agriculture by modern foods will become available for other uses. Given the sheer scale of the acreage in question, even low-intensity land uses such as reforestation will create hundreds of thousands of new jobs.

## Security of Supply

Raising livestock comes with inherent risks in the supply chain, particularly from animal disease outbreaks such as Mad Cow[189] and Foot and Mouth[190], Avian Flu[191], and African Swine Fever. When outbreaks occur, they are accompanied by livestock culls, loss of consumer confidence, trade restrictions, domestic control measures and, sometimes, human health concerns, all of which affect farmers, industry, international trade, tourism, biodiversity, and the economy.

Currently, African Swine Fever is raging across Asia. Nearly four million pigs have been culled to date, which has already caused pork prices to increase by 40% globally. By the end of the year, Vietnamese and Chinese pork production are forecast to fall by 10% and 35% respectively.[192]

Clustering, confining, and stressing enormous animal populations makes industrial agriculture highly susceptible to disease outbreaks. Dependence on a vulnerable supply chain puts farmers, businesses, and the general population at risk financially.

In stark contrast, modern production methods will use a diverse, distributed, and localized supply chain. Production facilities will be controlled environments that are independent of one another, so a shock to one facility will not affect others. This will make for a much more stable, secure supply chain.

## Resilience

Most cities and regions do not have the resources or capacity to feed their populations longer than a few days, presenting risks if there is a natural disaster, a power outage, or geopolitical conflict, for example. Decentralization of the industry will bring food production to cities, increasing their autonomy and improving resiliency. Equally, more remote communities will no longer be wholly reliant on importing food but could provide for themselves more easily and reliably.

## Greater Transparency

There have been public backlashes over supply chain-related controversies in agriculture such as Pink Slime, Mad Cow disease, animal abuse, and GMOs.[193] These have brought improvements in labeling as well as changes to laws and regulations regarding the treatment of animals. However, many segments of the industrial animal-agriculture industry are opaque. Certain anti-whistleblower laws across the U.S., referred to as "ag-gag laws", enable the industry to prohibit any reporting of bad practices. In modern production, transparency will be vital, with companies already being open about the ingredients and processes that make up their products in an effort to gain consumer confidence and prime the market for launch. As the more transparent companies succeed, incumbents will have to be more transparent in order to compete. The overall outcome will be a far more transparent food chain.

## Animal Welfare

Worldwide, there are more than 74 billion farmed animals.[194] In the U.S. alone, 9.5 billion animals are slaughtered each year for food, the vast majority (95%-99%) of which are raised on industrial farms.[195]

These farms, or CAFOs, are often criticized for the mistreatment of animals due to confinement, crowding, over medication, forced reproduction, abuse, and inhumane handling. In response, some states, corporations, and organizations have begun to address these concerns with policies and legislation, including phase-outs and bans of battery cages for hens, gestation crates for sows, tail-docking cattle, and the excessive confinement of veal calves, as well as the repeal of anti-whistleblower laws.[196]

By removing live animals from production, concerns about the treatment and slaughter of animals raised for food and other animal-derived products will cease to exist.

## Global Impact

The modern food disruption will lead to rapidly-shrinking markets and dramatic loss of income for livestock producers. Internationally, this means major producers of animal products are at risk of a serious economic shock. Countries that produce large quantities of conventional animal products and inputs to animal agriculture like Brazil, where more than 21% of GDP comes from agriculture, 7% of which is from livestock alone,[197] are particularly vulnerable. The U.S. is a top exporter of multiple animal products including beef, poultry, eggs, pork, milk, corn, DDGS, soy, soybean meal, and animal pellets (though together these make up less than 5% of total exports).[198] Following the modern food disruption, demand for these products will fall dramatically, both within the country and around the world.

On the flip side, countries importing these products will benefit as they can more easily produce these products domestically at a lower cost. Major importers of animal products such as China, South Korea, and Japan will benefit from both these cost savings and increased food security and resiliency. The ability to produce low-cost, high-quality food in close proximity to consumers will also bring increased food security in low-income countries such as Afghanistan, Burkina Faso, and Burundi.[199]

As countries begin to localize production of food, the need for international trade of staple foods will diminish, as will the ability to use food as a tool of influence and control.

Countries that lead the disruption will also be able to grow their influence indirectly by creating major industries that generate jobs, wealth, and export opportunities in technology, intellectual property and food, thereby increasing their economic power. Large endowments of arable land and other natural resources are not required to lead the disruption, so the opportunity exists for any country to capture value associated with a global industry worth hundreds of billions of dollars that ultimately emerges over the course of this disruption.

## Part Four

# Choices and Planning

The key agents of change in this disruption are policymakers, investors, businesses, and consumers. The choices these groups make influence each other and affect the speed of adoption of modern food technologies and the disruption of industrial agriculture. The choices made will determine whether society can seize the full potential benefits of this disruption.

The economics of modern food technologies are such that the disruption will play out regardless of the actions taken by each group in any single country, but these groups do have the power to speed up or slow down adoption of the new technologies. We believe the opportunities for businesses and investors to create wealth, for consumers to buy cheaper, healthier food, and for policymakers to enable extraordinary economic, health, social, and environmental benefits mean each group will embrace these technologies far quicker than the current mainstream narrative suggests.

## 4.1 Policymakers

Policymakers have many tools at their disposal to accelerate or delay the disruption, as well as to capture the benefits and mitigate the potential downsides of the new food system, such as job losses and the severe impact these could have on local farming communities. The broader benefits of the new system to society are so profound that we expect a global race to the top as countries look to capture the wealth, health, and jobs that will come to those that lead the disruption.

Emerging technologies have the potential to create a distributed, open-source, low-cost food system in which entrepreneurs anywhere will be able to design and produce foods with relatively low barriers to entry. However, a disruption that realizes all the potential benefits is not a foregone conclusion. In particular, poor decisions regarding IP regimes and product approval processes could lead to an industry with high development costs, restricted IP, and high barriers to entry, which would stifle innovation and slow adoption. Countries that follow this path will see themselves overtaken by others that remove barriers and encourage investment.

Starting today, the choices that policymakers make, therefore, will determine whether their societies capture the full benefits from the modern food disruption.

Here, we summarize some of the tools available to them:

### Intellectual Property

Patents are government-sanctioned monopolies. They are designed to offer a temporary monopoly to help attract investment for product development that would otherwise not be made. Once the patent expires, the monopoly ends and the benefits of it accrue to all members of society. An industry like pharmaceuticals requires large investment and long development and approval times to deliver drugs, so the IP regime provides companies with the certainty that, if they successfully develop a new drug or process, they will be able to reap the benefits without competition, at least for a few years. The result of pharma-type IP protection is that there are only a few new drugs on the market and they can cost hundreds of thousands or even millions of dollars per patient, per year. An IP regime like the pharmaceutical industry would slow progress and erect unnecessary barriers. It could also create an oligopoly-type structure through which a few large companies would control the food system. Clearly this is not what the world needs for the modern food industry.

The costs of developing new molecules are already relatively low and are falling fast. This means the new industry lends itself to a completely different model, more akin to the software industry, which has enabled the creation of orders-of-magnitude more knowledge, applications, and content at little or no cost to consumers. Countries that recognize that Food-as-Software needs a more open, transparent, and permissive IP regime will out-compete those that do not.

#### Recommendations

» Allow companies to patent production methods but not life, genes, or molecules – IP regimes should be process-focused rather than output-focused. This will encourage innovators to adopt and develop the technology and encourage the development of open-source platforms and molecular, cellular, and biological system databases.

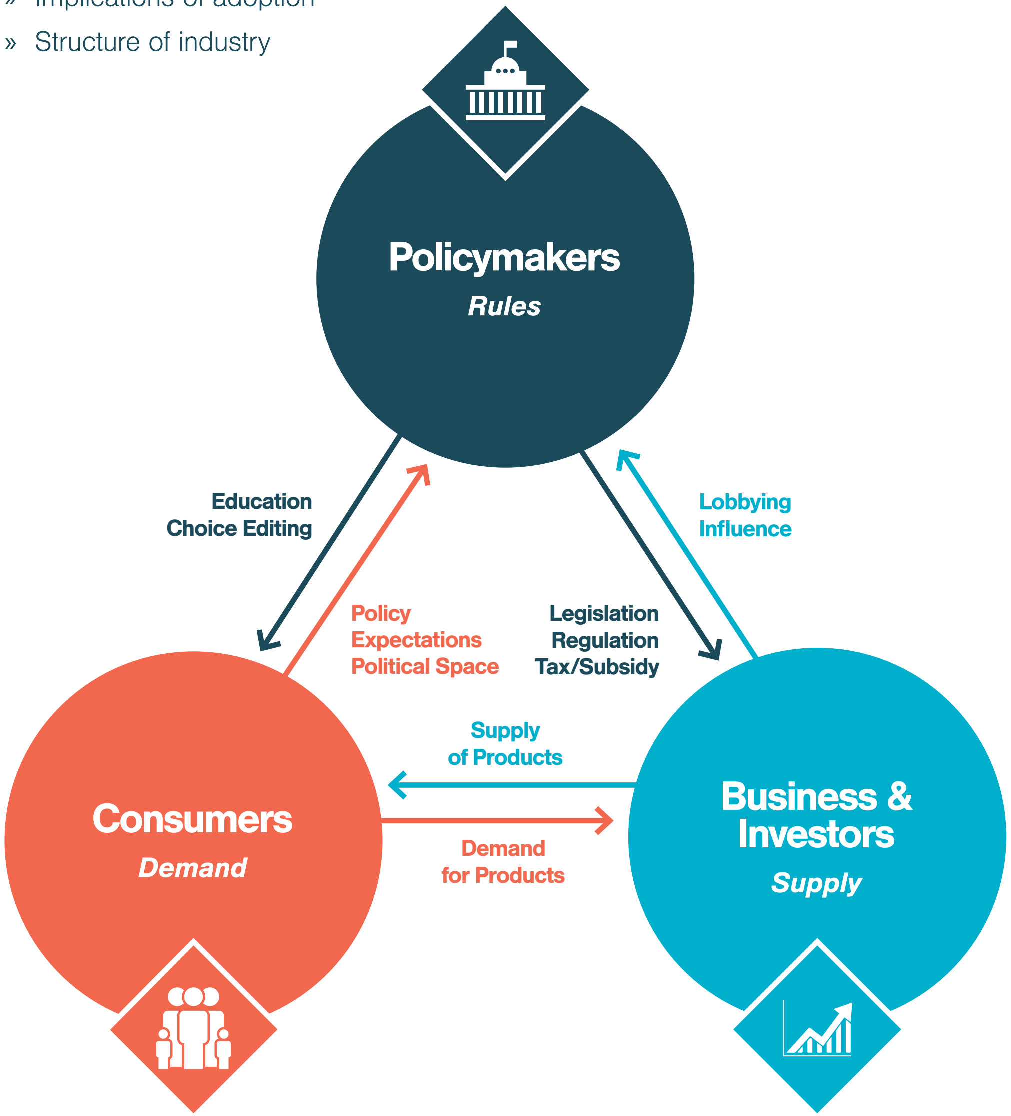
» Avoid following the pharmaceutical model when implementing IP regimes because, unlike drug development, the cost of product development via modern food production is already relatively low and falling fast.

» Support the creation of open-source, transparent, collaborative networks – preferably international – to accelerate the pace of development.

## Figure 27. Key Levers for Decision-makers

**Choices each group makes influences:**

- » Speed of adoption
- » Implications of adoption
- » Structure of industry




*Source: RethinkX*

## Food Regulation

New food products need approval from the FDA or USDA. This regulatory system can be used to erect barriers to slow down or even ban new products, but it can also be used to accelerate their adoption. As we have seen, there are many wide-ranging benefits to modern foods that provide a powerful incentive for policymakers to support their adoption.

Food regulation is crucial to ensure public health and safety, so precautions need to be taken to ensure that all foods are healthy and safe to eat. Policymakers will, therefore, need to find a delicate balance between health and safety (which are non-negotiable) and the rapid adoption of modern foods.

Regulation should apply to both conventional and modern foods. That is, rules for food safety, clarity, and transparency should apply to animal-derived as well as modern food products and manufacturing processes.

### Recommendations

- » Accelerate the disruption by updating and streamlining evaluation processes for modern food products and their ingredients, incorporating new methods such as computer simulation to understand the impact of foods on human health.
- » Increase transparency by modernizing food labeling to better communicate health benefits, health risks, and environmental impacts to consumers. Labeling laws should have clear meanings. For instance, the word ‘natural’ does not have a clear legal meaning today and can be used by food marketers to mislead consumers.
- » Establish an independent regulatory body to develop policies and oversee modern food technologies and their products, given the lobbying power of the conventional food industry and potential conflicts of interest between the old and new industries.

### Financial Incentives and Taxes

Industrial agriculture is currently heavily subsidized and the agriculture lobby exerts significant influence on policy.[200] Government regulation currently keeps the industrial dairy and beef industries afloat through subsidies, surplus storage, product re-distribution, and marketing. Without these practices, these industries would struggle to survive. They distort the market and artificially drive down dairy and beef prices, which raises the barriers to innovation and makes it more difficult for new products to compete with and undercut the costs of protected industrial products.[201]

#### Recommendations

- Enable well-regulated markets but do not participate in or distort the food or agriculture business. For instance, today the government stockpiles 1.4 billion pounds of cheese that it pushes in the form of school lunches and the Supplemental Nutrition Assistance Program.[202]
- Price negative externalities by taxing the most damaging and unhealthy products to reflect their broader costs to society.
- If necessary, provide producer subsidies for foods based only on whether they present clear food security, public health, and environmental benefits, irrespective of their method of production.
- Consumer food subsidies should be based on need and be independent of food industry sources.
- Create debt-relief programs to help small businesses, individual and family farmers, and others within the value chain to exit their incumbent industries.
- Expand social safety-net programs to ensure that individuals affected by the modern food disruption can either retrain for other livelihoods or retire with dignity.
- Protect people, not companies or legacy industries.

Policymakers have many financial tools available to influence the speed of adoption of modern foods, including direct taxes, subsidies, tax breaks, investment credits, soft loans, and sales tax rates. These tools can be used to ensure that foods with the greatest benefit to society are supported and their adoption encouraged, while those with negative impacts are discouraged and penalized. Measures can also be taken to mitigate the most severe impacts on stakeholders in the incumbent food system.

### Public Awareness and Transparency

Consumers are likely to face conflicting information and disinformation about the relative merits and safety of modern food versus traditional animal products. Currently, some regulations seek to dampen directly demand for new products by restricting what the products can be called in the marketplace. In some jurisdictions, such as Missouri, Louisiana, and France, words like ‘milk’, ‘cheese’, ‘meat’, and ‘bacon’ can only be used to describe products that come from slaughtered animals. Authorities cite consumer confusion as motivation, but the evidence indicates that consumers know the difference between almond milk, cow milk, and the Milky Way. Powerful industry lobbying is more likely to be creating false narratives.[203] Policymakers can ensure that consumers are able to make well-informed choices by ensuring that accurate information is readily available to the public, with clear and consistent rules around labeling.

#### Recommendations

- Establish an independent regulatory body to evaluate and disseminate information about modern food technologies and their products.
- Establish clear, official terms and definitions in conjunction with the food industry, both old and new, that government agencies use when referring to various products and their production methods that do not favor one industry over another.
- Establish clear transparency and disclosure requirements that apply equally to products and production processes across all relevant industries.
- Prioritize consumers’ right to know – instead of simplistic food labels, consumers should be able to scan a QR code that shows details of the content of food they intend to purchase, including the source of all ingredients, manufacturing methods, heavy metal content, health impact to children and adults, and environmental impact.

### Land Use

The enormous swathes of land freed from agricultural use and the resulting collapse in value will represent an unprecedented, one-time opportunity to reimagine fully one-quarter of the American landscape, an opportunity similar to the Louisiana Purchase of 1803. It is vitally important that this opportunity be used wisely to strike the best balance between competing interests and to deliver an outcome that works for society as a whole.

### Recommendations

- Create a national vision for repurposing this freed land, based on an analysis of potential future needs and uses.
- Update planning regulations to reflect the desired social outcome.
- Create a new independent body to oversee and manage this challenge in order to avoid conflict among existing agencies with competing purviews and priorities, including national, regional, and local interests.
- Recognize that this opportunity will become a source of political conflict between developers, environmentalists, farmers, and other industries and actively engage all stakeholders from the outset.
- Anticipate that whole towns and regions will be disproportionally affected by the disruption and enable programs to help local populations transition successfully to the new food system. This includes providing educational, financial, healthcare, and social-capital support, as well as creating new employment opportunities.

## 4.2 Businesses and Investors

As we have seen in Part 3, businesses along the value chain of livestock farming – in supplying inputs, production, processing, distribution. and retail – will be profoundly affected by the modern food disruption. The outcome for them will depend on the choices they make over the coming decade. In some parts of the value chain, there will be little choice but to exit the business to avoid value destruction. In other parts, adaption will be possible. Recognizing the potential speed and scale of disruption will allow businesses, and investors in them, time to adapt and take actions to mitigate any losses. The choices available depend on the scale of disruption to different parts of the value chain and the ability of individual companies to adapt.

### Landowners and Livestock Farmers

The right strategy depends on the location and productivity of the land, as well as the value of alternative uses and restrictions on land use (see Part 3). Some land will continue to be used for pasture or arable crops but, given that an oversupply of available land will see land values drop significantly, selling before the full impact of the disruption takes hold may be the best way forward.

Less productive land far from cities will not be needed for food production. If there is low amenity value or no high-value alternative use, then selling early might again be the best strategy. In the meantime, landowners and farmers should cease investment and maximize profits and cash flow.

Land near cities might have use as industrial, commercial, or residential land, subject to planning changes, and could see an increase in value. Holding and petitioning for regulatory land use change, therefore, might be the best plan.

Industrial feedlots will see volumes shrink rapidly and capacity utilization drop, leading to a need for consolidation, but this process will do little to help improve the longer-term valuation as volumes continue to drop.

### Suppliers of Inputs (feed, pesticides, fertilizer, and antibiotics)

As discussed in Part 3, the volume of inputs will decline in line with the number of animals or the amount of land used. However, revenues and profits will be affected disproportionately, as will prices of inputs. Businesses should rethink plans to invest in new capacity and either sell existing capacity or begin to maximize cash flows. Focusing on cost management might allow businesses to thrive as low-cost suppliers.

### Processors (slaughter and rendering)

By the mid-2030s, remaining demand for livestock is likely to be for meat only and will be met largely through artisanal, pastural production. Businesses involved in processing should consider selling early or splitting off the relevant business units. If this is not possible, ceasing investment and maximizing short-term returns is likely to yield the best return.

### Distribution and Retail

Businesses in this part of the value chain have the potential to adapt and thrive in the emerging system. They also have the potential to vertically integrate and become involved in food production in the new, decentralized system. Businesses that succeed will need to rethink their existing structures and processes and learn to cope with rapid change. The new model of Food-as-Software means these businesses need to see themselves as technology companies. Brand, trust, cost, and convenience will be the key to competitive advantage.

### Investors

Investors in many businesses in the existing industry should face an easier challenge. Selling is always an option if there is sufficient liquidity. The timing of adoption of modern foods and the collapse in value in conventional food production companies may be uncoupled and thus uncertain, so selling early seems sensible. However, there is often a boom before the bust. As companies cease to invest, supply might fall and profits rise in the short-term, giving the impression of an opportunity. Any rebound like this could be a good time to sell.

Picking individual winners is harder than identifying losers, however the disruption will create extraordinary opportunities if investors are aware of where value will be created, which is not always in obvious places. For example, as solar PV has grown exponentially, solar panel technology companies have provided poor returns while financiers and developers have performed better. In the modern food system, opportunities will be created in many areas including biotechnology, software, fermentation farms, and food distribution (see Part 3).

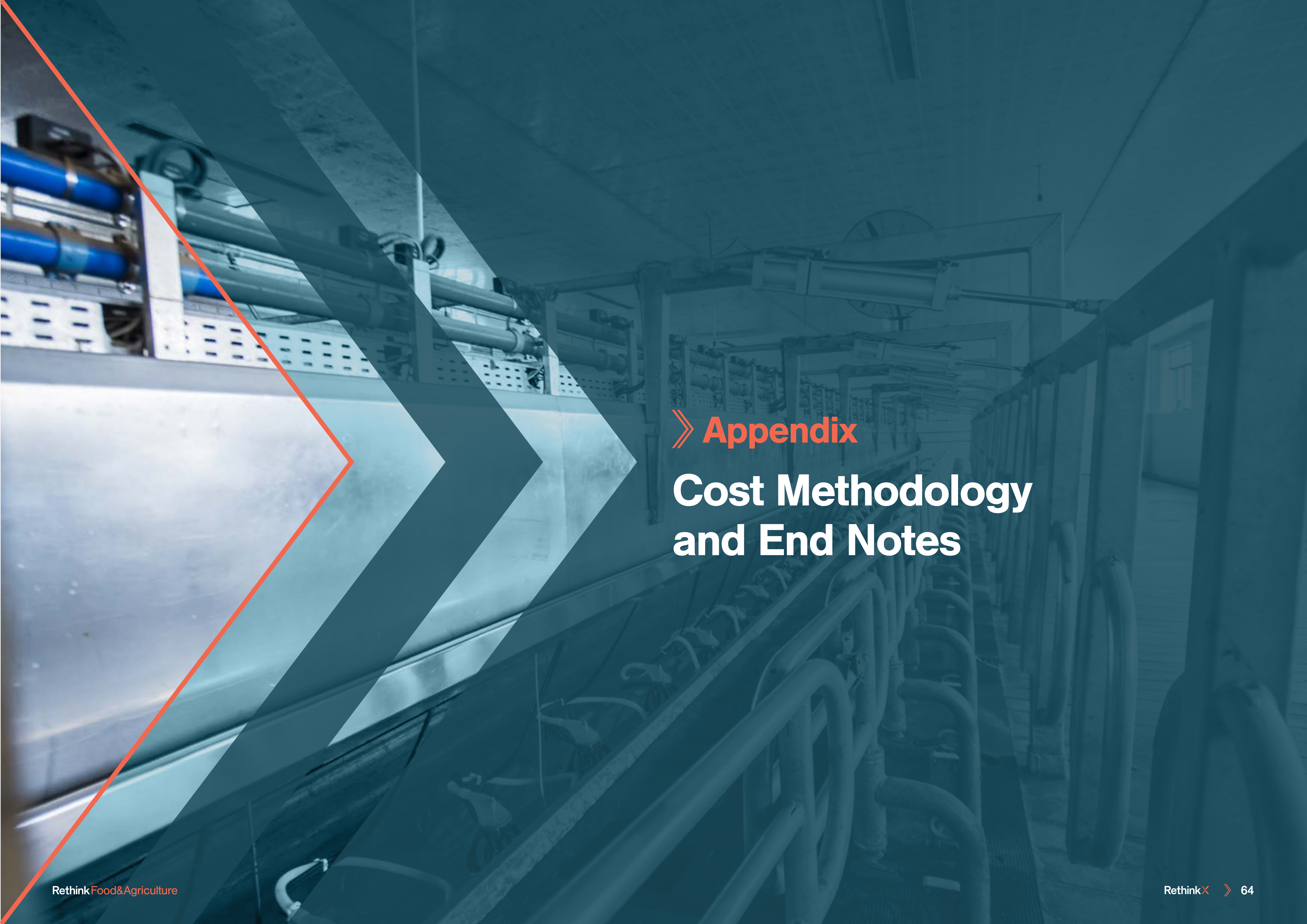
## 4.3 Civil Society

Consumers will be driven by the factors we discuss in Part 2. However, they will also be influenced by media coverage of these new technologies. We would expect businesses involved in industrial livestock farming to try to influence consumers through scare stories, pseudo-science, and other tactics that try to cast doubt on the benefits of modern foods.

NGOs and other civil society organizations will play an important role in the adoption of modern foods through their influence on policymakers, businesses, and consumers. They must strive to understand the relative benefits of the modern system over the industrial system and ensure their interventions are based on rigorous analysis. They have the potential to act as a counter-balance to vested livestock interests in influencing public opinion.

This influence could ensure that the full benefits of the emerging food system are realized across society. However, thinking rooted in the old system, such as environmentalists equating incremental changes like 'sustainable grass-fed' agriculture as 'good' and industrial production as 'bad', will need to adapt. Both these systems are hugely inefficient compared to the modern food system and have already reached their productive potential.

Only by breaking out of the agriculture system of the first domestication of plants and animals can we hope to ensure a food supply that is abundant, accessible, healthy, inexpensive, and nutritious, without the destructive environmental impact of our current system. The second domestication offers extraordinary economic and social advantages and represents the single greatest opportunity for environmental recovery in human history. By making the right choices today, we can ensure these tremendous benefits accrue to each and every one of us.



## Appendix

# Cost Methodology and End Notes

# Appendix: Cost Methodology

## Introduction

Here, we show our assumptions for the cost of protein production by our core technology of precision fermentation (PF). Low costs and increasing capabilities will mean rapid adoption of products, starting with business-to-business (B2B) ingredients before reaching end consumer products.

## Precision Fermentation

### Historical Costs

» PF has been around in its earliest form since the 1970s, although our first data point is from the 1980s.

» Cost data is sparse, but costs have been falling exponentially, driven by continuing waves of competitive convergence in biotechnologies over the last decades (Figure 28).

» We estimate costs have fallen 10,000,000 times since the first molecules were produced, to about $100/kg today. An order of magnitude reduction to about $10/kg will unlock the market for food products.[204]

### Future Cost Analysis

» We use a mixture of bottom-up and top-down (extrapolation of the cost curve) modeling due to the relative nascence of some of the technologies involved.

» We anticipate exponential cost improvements will continue as we enter a new age of precision biology, resulting in further cost improvements.

» Our analysis is based on key areas:

- **Feedstock**. Our analysis uses sugar (glucose) as the main feedstock, with efficiency trending from 3kgs of feedstock per 1kg of protein produced (a conversion ratio of 3:1) toward a ratio of less than 2:1 by 2030. There is also scope for other carbohydrates to be used for feedstock.

- **Capital costs.** For fermentation tanks, our analysis uses baseline data from Quorn, other industry data, and discussions with experts. We also take into account recent advances in fermentation tanks.

- **Operating costs**. For fermentation tanks, our analysis uses baseline data from Quorn, alongside our own assumptions of fermentation tank sizes, utilities, and other operating costs.

- **Scale-up**. The speed of scale-up is one of the biggest unknowns as most of the companies in this sector are startups. The scale-up speed will depend on capital investment, and the ability to repurpose and capture current infrastructure and talent (such as from bioethanol or beer producers). As with most technologies, the cost of marginal production depends largely on the cumulative experience the industry has with producing the relevant technology. This relationship is expressed as the 'experience curve'. Essentially, every doubling in the cumulative number of units of a given technology reduces the cost of producing one additional unit by a given percentage.

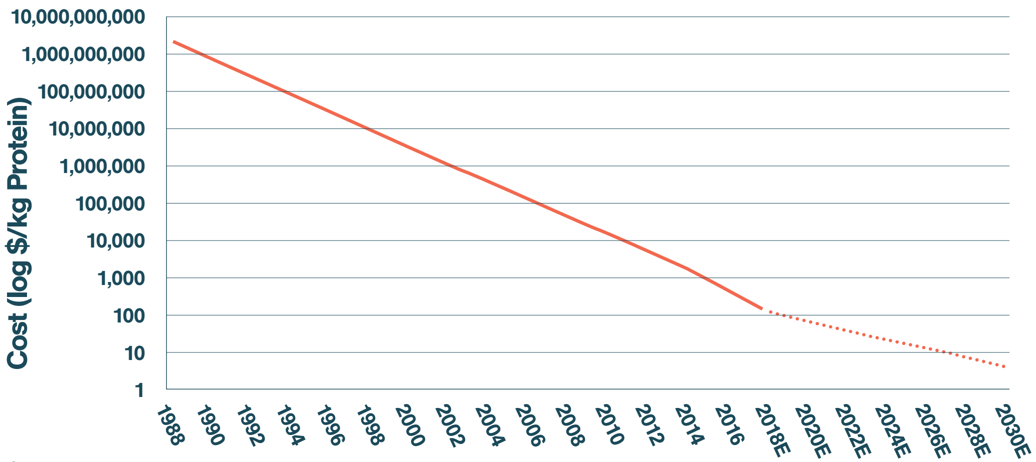
  The scale-up of technologies will, therefore, help drive costs lower. Currently, large-scale PF means production on the scale of grams to a few kilograms. This disruption will ultimately require millions of tons of production. Some of the biggest fermentation tanks used today are bigger than 100,000 liters, but those used for PF are in the region of 5,000 liters (the largest are for enzymes). This production is optimized for the current biological standards. However, we expect further improvements in these processes as the technologies improve. For example, Stämm have developed a high-throughput continuous process that has improved productivity by 74 times.[205]

» **Cost forecasts.** Figure 29 presents our cost curve for 1kg of protein. However, products each contain varying amounts of proteins. As such, end products will have different cost curves.

- Between 2023-2025, PF protein hits $10/kg.

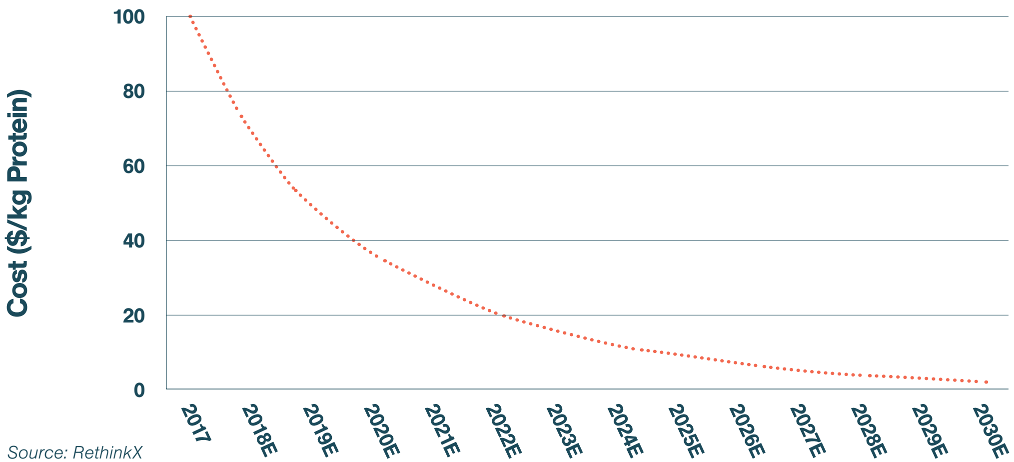
- By 2035, PF protein will be $1/kg.

## Figure 28. PF Costs: Historical and Forecast




Source: RethinkX

## Figure 29. PF Cost Forecast




Source: RethinkX

### Implications for Other Technologies

» Falling PF costs will enable other technologies such as cell-based production. The affordability and viability of cell-based beef is dependent on PF (see Box 14).

### Other Assumptions

» Our experience curve for PF proteins will be driven by the production of all PF proteins. So, PF dairy proteins will also drive the experience curve for PF heme or collagen.

» We give a date range as the data is not widely available.

» We assume continued scale-up. Currently, a large PF batch would be in the order of 1kg to a few tons.

» The size of fermentation tanks currently employed are around 5,000, 10,000, and 20,000 liters.

» As long as 100,000 liter (modular) is within the realm of possibility, we are comfortable assuming that scale-up is possible/inevitable and that the main/only barrier is capital.

### Product Cost Analysis

» Cost curves will be different for every product containing PF, as the number of possible formulations of these products using PF is infinite.

» The disruption will happen in four waves as we discuss in Part 2.

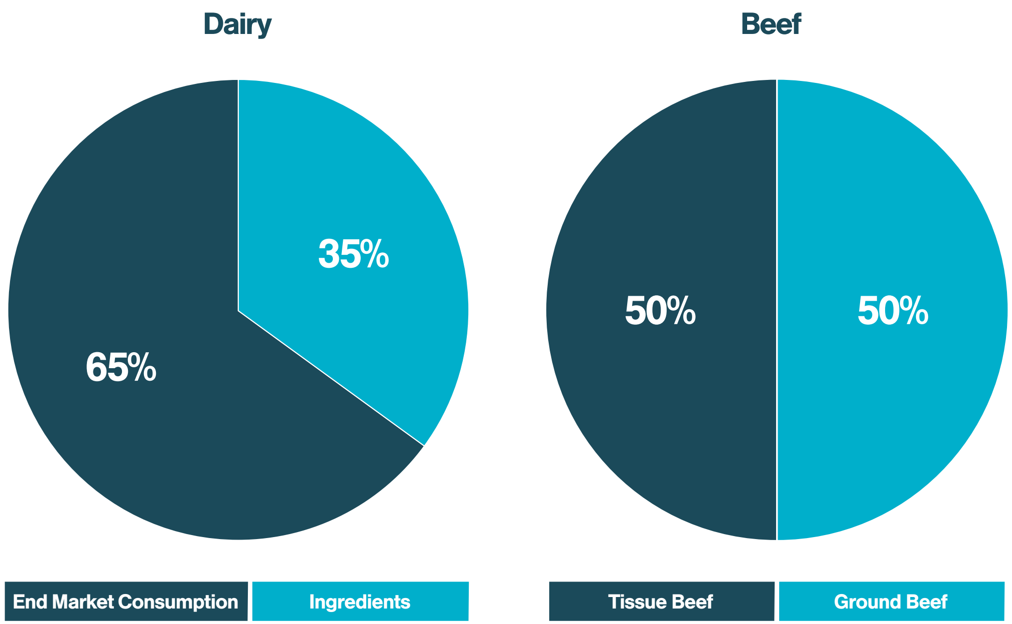
» These four waves encompass different types of product.

» To model these for dairy and beef, we split the markets as shown in Figure 30.

» This is a B2B ingredient-led disruption, where decisions to use PF products will be made by businesses, not consumers.

» As such, we identify the dairy ingredients and ground beef markets as the key areas of disruption.

## Figure 30. Beef and Dairy Market Splits




*Note: Sales of ground beef are estimated at between 40%-60% of total beef sales. We use 50%, but the market can react to demand*

*Source: RethinkX*

# Dairy

### Market Led by Ingredients

» The cost of marginal production depends strongly on the cumulative experience of producing the relevant product.

» Demand for PF products drives the rate of producing PF products, which in turn increases the cumulative amount of PF products ever produced.

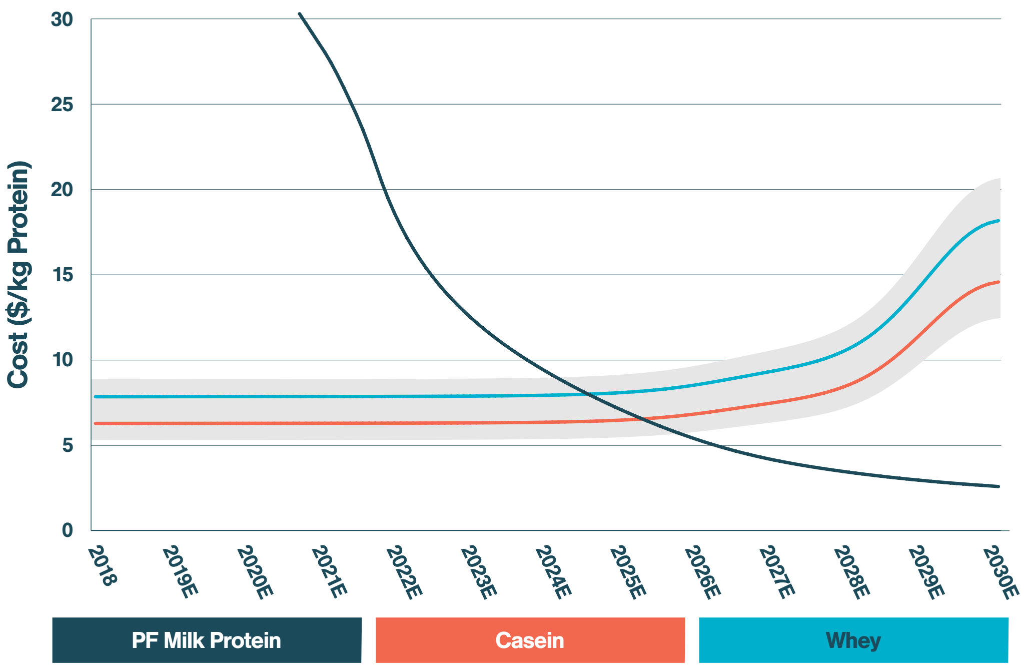
» The cost of PF-enabled dairy proteins will reach $10/kg, the wholesale cost of dairy proteins, in 2023–2025.

» By 2030, the costs of these PF proteins will have dropped even further, while at the same time the cost of cow-produced milk proteins will have doubled, so that PF-enabled dairy proteins are 50%-80% lower than cow-produced whey and casein (Figure 31).

» Negative feedback loops triggered by lower demand for cow-based products will lead to higher costs, leading to consolidation and then bankruptcies.

» The doubling in cost of cow proteins is a conservative estimate – the rise could be more (or less) depending on how quickly the system collapses. The higher the multiple of the cost, the more painful the collapse of the conventional system will be.

## Figure 31. The Cost of PF Dairy



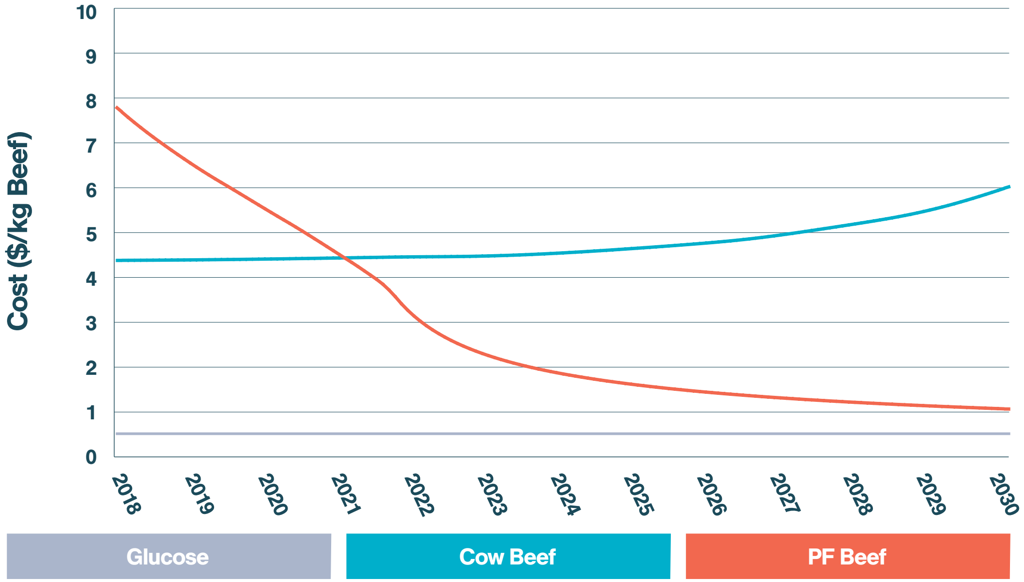

*Source: RethinkX*

## Beef

### Market Led by Ground Beef Disruption

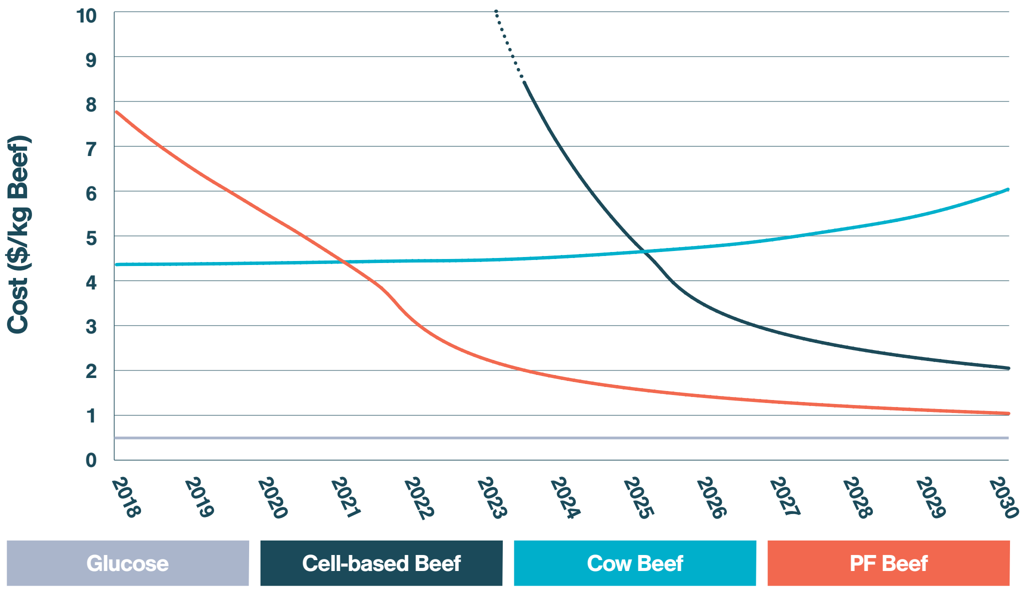
- We model total beef disruption under two scenarios:
  1. PF-enabled disruption only (no cell-based beef is available commercially before 2030).
     - Products reach cost parity with conventional meat in 2021 and are six times lower in cost by 2030.
     - The PF content continues to increase during the ramp-up phase, from 2% today, to 10% in 2021 (mid-year), to 35% in 2023 (mid-year). Ultimately, we expect the PF content of PF-enabled ground beef to approach an upper protein plus fat threshold of 40%. This is for our analysis only and not a conclusion on what the optimal PF content is going to be – we are likely to see many recipes.
     - Conventional meat costs will double by 2030.
  2. Includes cell-based beef and PF-enabled disruption.
     - For more information on the cost curve for cell-based meat, see Box 14.
     - PF-enabled content is shown above.
     - The first commercially available cell-based ground beef is available in 2022, and the first tissue beef in 2024
     - Cell-based content of beef starts at 10% for the initial products before rising to 100% by 2025.
     - Cell-based meat products reach cost parity in 2025 and by 2030 are three times lower than the cost of conventional meat.
     - Because cell beef is a direct substitute for animal beef, this transition is much more cost-sensitive and, therefore, will happen faster.
- Costs of conventional meat increase in both scenarios due to a shrinking market for meat. As with other commodities, selling less product results in a higher per-unit cost as a lower sales volume must support a larger per-unit amount of processing infrastructure.

**Figure 32. Cost of PF-enabled Beef vs. Cow Beef**




*Source: RethinkX*

**Figure 33. Cost of PF-enabled Beef and Cell-based Beef**




*Source: RethinkX*

# Box 14: The Cost of Cell-based Beef

- Cell-based meat production technology is different to PF in that it produces actual muscle cells.
- Unlike PF, as of writing, cell-based meat products are not commercially available. As such, there are more technology constraints on the commercialization of cell-based meat, such as on scale-up and scaffolding to make tissue meat.
- Falling costs of PF will enable the commercial production of cell-based meat, as it can be used to produce some of the key proteins in the currently high-cost medium (such as growth factors).
- Our cell-based meat cost model utilizes the work done on medium cost by the Good Food Institute (GFI), but we include our forecasts for PF in the key cost of the medium.
    - The cost of the medium in cell-based meat currently represents the single biggest cost – probably 80%-90% of the marginal cost. Analysis by GFI indicates that no breakthrough technology is needed for the cost of cell-culture nutrient media to fall by "several orders of magnitude".
    - Some of the key components of the medium are proteins that could be made using PF, and applying our PF cost forecasts alongside GFI's analysis suggests the cost of the medium could fall by 4,000 times, from about $400/liter today to less than $0.10/liter by 2030, due both to the scale-up of production and the intentional decline in product quality from pharmaceutical-grade to food-grade.
- **Cost forecasts**. Figure 33 presents the cost curve for 1kg of ground beef made using cell-based agriculture (which does not require product structuring and scaffolding).
    - Between 2023-2025, cell-based ground beef will hit $10/kg.
- **Other technology constraints**. While the cost of the cell media poses the largest immediate challenge, other more technical challenges remain concerning the development of cell lines, scale-up, and product scaffolding and structuring. Due to the technical nature of these problems, less is known about the cost parameters.
    - Cell-line development (or the starting cells containing the genetic information) will have a direct impact on the ability of the cells to grow into meat. Cell lines can define how quickly the cells double and grow, as well as the taste and nutrition of the end product.
    - Scale-up will depend heavily on the design of the fermentation tanks and the types of process (batch, semi-continuous, or continuous).
    - The process of how products will achieve structure and scaffolding still has various options, ranging from seeding onto scaffolds at different points in the growth phases to 3D printing of cells. We anticipate challenges will be overcome with investment. The cost of scaffolding is likely to vary for different product types (steak, legs, or ribs). This is why many of the first products have focused on ground meat products that do not have the same challenges as more structured cuts of meat.

# End Notes


1 When viewed as a protein ingredient production system, both dairy and beef cows are highly inefficient. According to Shepon's research, dairy cows convert only 14% of the protein they consume into edible human protein, and beef cows only 3%. Any production system that destroys value to this extent is a disruption waiting to happen. Shepon, A., Eshel, G., Noor, E., & Milo, R. (2016). Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environ. Res. Lett.,* 11(10). Retrieved from here.

2 de Ondarza MB. (2004). Protein. *Milk Production.* Retrieved from here.

3 Price does not equal cost. The price of, say, meat can be higher than individual molecules despite lower processing costs. This is because other products are byproducts.

4 Brunning, A. (2014, September 16). A Brief Guide to the 20 Amino Acids. *Compound Interest.* Retrieved from here.

5 Milo, R. & Phillips, R. (2015, July). Cell Biology by the Numbers: How Big Is The "Average" Protein? Retrieved from here.

6 Green, A. (2018, March 15). Saving Lives with Platypus Milk. *CSIRO.* Retrieved from here.

7 Trafton, A. (2018, May 21). Chemists Synthesize Millions of Proteins Not Found in Nature. *MIT News Office.* Retrieved from here.

8 Biology is now done in both 'dry' (computer) and 'wet' (lab) conditions. A researcher can quickly conduct hundreds of thousands of chemical, genetic, or pharmacological tests a day using robotics, data processing and control software, liquid handling devices, and sensitive detectors. This high-throughput screening allows scientists to prepare, incubate, and analyze many plates simultaneously, further speeding up the data-collection process.

9 Schwartz, A. S., Hannum, G. J., Dwiel, Z. R., Smoot, M. E., Grant, A. R., Knight, J. M., ... & Richardson, T. H. (2018, July 10). Deep Semantic Protein Representation for Annotation, Discovery, and Engineering. *bioRxiv.* Retrieved from here.

10 CRISPR-CAS9 allows us to edit DNA in a cell cheaply, rapidly, and accurately. National Institute of Health (NIH), United States National Library of Medicine. (2019, May 14). What are Genome Editing and CRISPR-Cas9? Retrieved from here.

11 NIH, National Human Genome. The Cost of Sequencing a Human Genome. Retrieved from here.

12 In 2017, Illumina announced their intent to reach $100 genome in *"more than three years and fewer than 10"*. Herper, M. (2017, January 9). Illumina Promises To Sequence Human Genome For $100 – But Not Quite Yet. *Forbes*. Retrieved from here.

13 TeraFLOPS, or trillion Floating point Operations Per Second, is a measure of computer performance. Seba, T. [Colorado Renewable Energy Society (CRES)]. (2017, June 9). *Clean Disruption – Energy & Transportation.* [Video File]. Retrieved from here.

14 PF is different to precision agriculture. Precision agriculture aims to extract more yield, revenue, and profits from the same patch of land providing, at best, a slight/marginal improvement. It is akin to making improvements in the film used in film cameras.

15 We define fermentation in a general sense, where the desired products can be the biomass, the intracellular or extracellular metabolites in the primary or secondary phases of growth, or the substrate that has been transformed.

16 Proteins are arguably the most important organic molecules to be produced for inputs across many consumer products. There are many different types of proteins, all of which have specific functions, including adding complex structure and texture, catalyzing reactions, and delivering nutritional and therapeutic value. Proteins are a major component of all living things and are classed into families with specific functions and with familiar names, such as collagen, whey, albumin, enzymes, and antibodies.

17 Insulin was commercially available in 1982. PF is called recombinant protein production in biology. Fraser, L. (2016, April 7). Cloning Insulin. *Genentech.* Retrieved from here.

18 Human Growth Hormone was commercially available in 1985. National Museum of American History. (2012, October 18). The Big Story Behind Synthetic Human Growth Hormone. Retrieved from here.

19 Chymosin was commercially available in 1990. Flamm, E. (1991). How the FDA Approved Chymosin: A Case History. *Nature Biotechnology.* (9). 349-351. doi: 10.1038/nbt0491-349

20 Biologics are pharmaceutical products that are made up of complex molecules isolated from, or produced by, micro-organisms, or plant or animal cells. Many are made using biotechnology methods (PF) and are used to treat many serious, difficult-to-treat medical conditions. Some examples of biologics include Humira (anti-inflammatory), Avastin (cancer treatment) and Avonex (Multiple Sclerosis). United States Food and Drug Administration (FDA). (2018, June 2). What are "Biologics" Questions and Answers. Retrieved from here. Stone, K. (2019, February 4). Top 10 Biologic Drugs in the United States. *The Balance.* Retrieved from here.

21 Vitamins produced using PF include vitamin C, B2, B12, D2, EFAs, K2, coenzyme Q10, pyrroloquinoline quinine (PQQ) and glutathione (GSH). Some can be produced using a combination of chemistry and PF, such as niacin or B3, B5, C, and L-carnitine.

22 Stanbury, P., Whitaker, A., & Hall, S. (2017). Principles of Fermentation Technology (3rd ed). Ch.12. *Butterworth-Heinemann*, Oxford, UK.

23 Fraser. (2016). Cloning Insulin. Retrieved from here.

24 Eli Lilly & Company said the initial cost of the new insulin would be higher than that for animal insulins available at the time. *''We expect the average daily patient cost to be between 50 and 55 cents a day for the treatment,''* spokesman Ronald Cusp said. *''That compares with between 26 and 30 cents. The long-term desire is that the cost will come down, but at this point we cannot speculate on just how far. The ultimate aim is to make it cheaper, however.''* Altman, L. (1982, October 30). A New Insulin Given Approval For Use In U.S. *New York Times.* Retrieved from here.

25 Human insulin was, in turn, disrupted by human insulin analogues that could last for different lengths of time. Now these analogues have more than 90% of the market. Lipska, K. J., Ross, J. S., Van Houten, H. K., Beran, D., Yudkin, J. S., FRCP, & Shah, N. D. (2015, June 11). Use and Out-of-Pocket Costs of Insulin for Type 2 Diabetes Mellitus from 2000 to 2010. JAMA, 311(22), 2331-2333. doi: 10.1001/jama.2014.6316

26 Blakely J. Smithsonian Libraries. *"In the maritime world, long before the ration of rum, weak beer on navy ships was the standard provision for sailors. Beer provided some nutrition*

*and needed calories while not harboring harmful micro-organisms."* Retrieved from here.

27 Motif FoodWorks is a company that aims to do just this, supplying ingredients to the whole industry by doing all the biotech work but not developing consumer food products themselves. Spun out of Gingko Bioworks. More information can be found here.

28 Gibbons, M. (2018, August). AlcheMeat – how the future of animal production rests with biochemistry. *The Biochemist (Food Production), Biochemical Society.* Retrieved from here.

29 Shike, D. W. (2013). Beef Cattle Efficiency. *Driftless Region Beef Conference.* Champaign, IL. Retrieved from here.

30 Soy leghemoglobin (heme) is a plant based heme-containing protein found in the root nodules of soybean plants. It is being used as a key ingredient in plant-based meat products from Impossible Foods (The Impossible Burger). Heme is the iron-containing molecule found in blood and animal tissue that makes meat taste like meat. Impossible Foods. Heme + Science. Retrieved from here.

31 These are enzymes occurring naturally in plants and microbes that mimic the activity of calf rennet. Yacoubou, J. (2008). An Update on Rennet. *Vegetarian Journal, 3.* Retrieved from here.

32 Yacoubou, J. (2012, August 21). Microbial Rennet and Fermentation Produced Chymosin (FPC): How Vegetarian Are They? *The Vegetarian Resource Group Blog.* Retrieved from here.

33 FPC has always been much more efficient than rennet. A recent breakthrough improving efficiency of the enzyme means just 1% will lead to 220 million kgs more cheese globally for the same milk input. Southey, F. (2019, April 3). 'Game changer' cheese enzyme increases yield by up to 1%: 'There is nothing on par with this'. *FoodNavigator.* Retrieved from here.

34 The wholesale price of sugar jumped from $0.27/kg to $1.23/kg between 1973 and 1974, and from $0.46/kg to $1.14/kg between 1979 and 1980.

35 HFCS-55 is high fructose corn syrup that contains 55% fructose. Kennedy, P. L. & Garcia-Fuentas. (2016). A Supply and Demand Estimation of the United States High Fructose Corn Syrup Market, 2016 Agriculture and Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2. Retrieved from here.

36 Troitino, C. (2018, November 8). Impossible Foods' Bleeding Burgers To Make Grocery Store Debut In 2019. *Forbes.* Retrieved from here.

37 For example, Burger King market the Impossible Burger based on health benefits (0mg of cholesterol). Burger King. (2019, March 31). The Impossible Taste Test, Impossible Whopper [Video File]. Retrieved from here.

38 In 2018, the lowest quartile of New England dairy farms made a loss of $447 per cow, with the average across all farms a loss of $40 per cow [net earnings]. Meanwhile, the number of dairy farms in the U.S. dropped by 6.8% from 2018 to 2019. Farm Credit East. (2019). Northeast Dairy Farm Summary 2018. Retrieved from here. USDA, National Agricultural Statistics Service (NASS). (2019, March 12). *Milk Production.* Retrieved from here.

39 Price volatility in the dairy market is inherent because of seasonal variability, the perishable nature of milk, global shifts in supply and demand, and government regulations. Since 2010, U.S. milk prices have ranged from $0.32/kg to $0.57/kg. USDA NASS. (2019). Prices received by month for milk. Retrieved from here.

40 Direct and indirect subsidies from the government, estimated at $0.27/kg of milk in 2015, enable U.S. dairy farmers to operate at a net loss, negating the need to earn a profit and protecting them from international price pressure. As U.S. milk consumption has steadily decreased, the government has been purchasing surplus production and storing it as cheese, periodically releasing it to market in the form of government food assistance and deals with corporations. For example, in early 2018, the dairy checkoff program Dairy Management Inc. (DMI) partnered with Pizza Hut to include 25% more cheese on their pan pizzas in an effort to release 70 million extra kilograms of milk per year to the market. The start of 2019 has seen the largest ever surplus of cheese in storage at almost 617 million kilograms. Grey, Clark, Shih and Associates. (2018). U.S. Federal and State Subsidies to Agriculture: Prepared for Dairy Farmers of Canada. Retrieved from here. Wallin, S. (2019, February 27). Checkoff's Pizza Hut Partnership Leads To 25% More Cheese On Pan Pizzas. *Dairy Management Inc.* Retrieved from here. USDA, NASS. (2019, March 7). *Cold Storage.* Retrieved from here.

41 Some of the companies and organizations that are most active in lobbying the government on issues facing the dairy industry include Land O'Lakes, International Dairy Foods Association, Dairy Farmers of America, National Milk Producers Federation, and Dean Foods. The Center for Responsive Politics. (2018). Dairy: Lobbying, 2018. *Open Secrets.* Retrieved from here.

42 Milk Facts. Milk Composition. Retrieved from here.

43 RethinkX estimates based on company and industry data

44 Whey and casein prices are volatile and have ranged from $7/kg to $12/kg for whey and $6/kg to $10/kg for casein in the past 10 years. Protein Market: Dairy Protein Market Trends and Outlook. *Blimling and Associates.* Retrieved from here. UN Comtrade. 350220 Milk Albumin [Data File]. *Trade Map.* Retrieved from here. UN Comtrade. 3501105000 Other Casein, Except Of Milk Protein Concentrate [Data File]. *Trade Map.* Retrieved from here.

45 Whey is a byproduct of cheese production and its use has grown in line with greater cheese consumption in the U.S. (cheese accounts for 40% of milk production today, up from 10% in 1950). United States Department of Agriculture (USDA), Economic Research Service (ERS). (2017). *Food Availability (Per Capita) Data System: Dairy Products* [Data File]. Retrieved from here. The data serve as proxies for actual consumption at the national level

46 Companies working on the production of milk proteins through PF include Perfect Day (U.S.) (casein and whey) and New Culture (NZ) (casein micelles for mozzarella cheese).

47 Sugar Prices – 37 Year Historical Chart [Data File]. *Macrotrends.* Retrieved from here.

48 There is plenty of opportunity in niche markets for this disruption. Specific animal milks could be produced for zoos, while specialty proteins could be added to milk for for a creamier froth.

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113 Total livestock feed consumption is about 515 million tons, 305 million of which is from crops (corn, soy, sorghum, barley, oats, wheat and hay). The cattle percentage of feed crop consumption is about 50%. Other sources of feed for cattle and other livestock include animal protein meals, mill byproducts, mineral supplements, and pasture. RethinkX estimate, USDA. (2017). *Agricultural Statistics 2017.* Washington, DC: United States Government Printing Office. Retrieved from here.

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