Industry Reports

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

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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 US 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 (PF), a process that allows us to program microorganisms 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.

Choices

The disruption of food and agriculture is inevitable—modern foods 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 decisionmakers' 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.

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Decision-makers must also recognize there are no geographical barriers to the food and agriculture disruption, so if the US 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 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.

An often-overlooked component of this first domestication is the vital role microorganisms played. Microorganisms exist naturally within macroorganisms, breaking down nutrient inputs to build useful outputs. For example, microorganisms 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 microorganisms as well.

One thousand or so years later, humans were manipulating microorganisms 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 microorganisms to a far greater degree than our ancestors could possibly have imagined. We can now unplug microorganisms entirely from macroorganisms 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 macroorganisms. The second will allow us to master microorganisms.

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, microorganisms produce these individual nutrients directly. Domestication of microorganisms, 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 (*Fig. 1*).

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.

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.

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.[4] 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.[5] 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.[6]

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

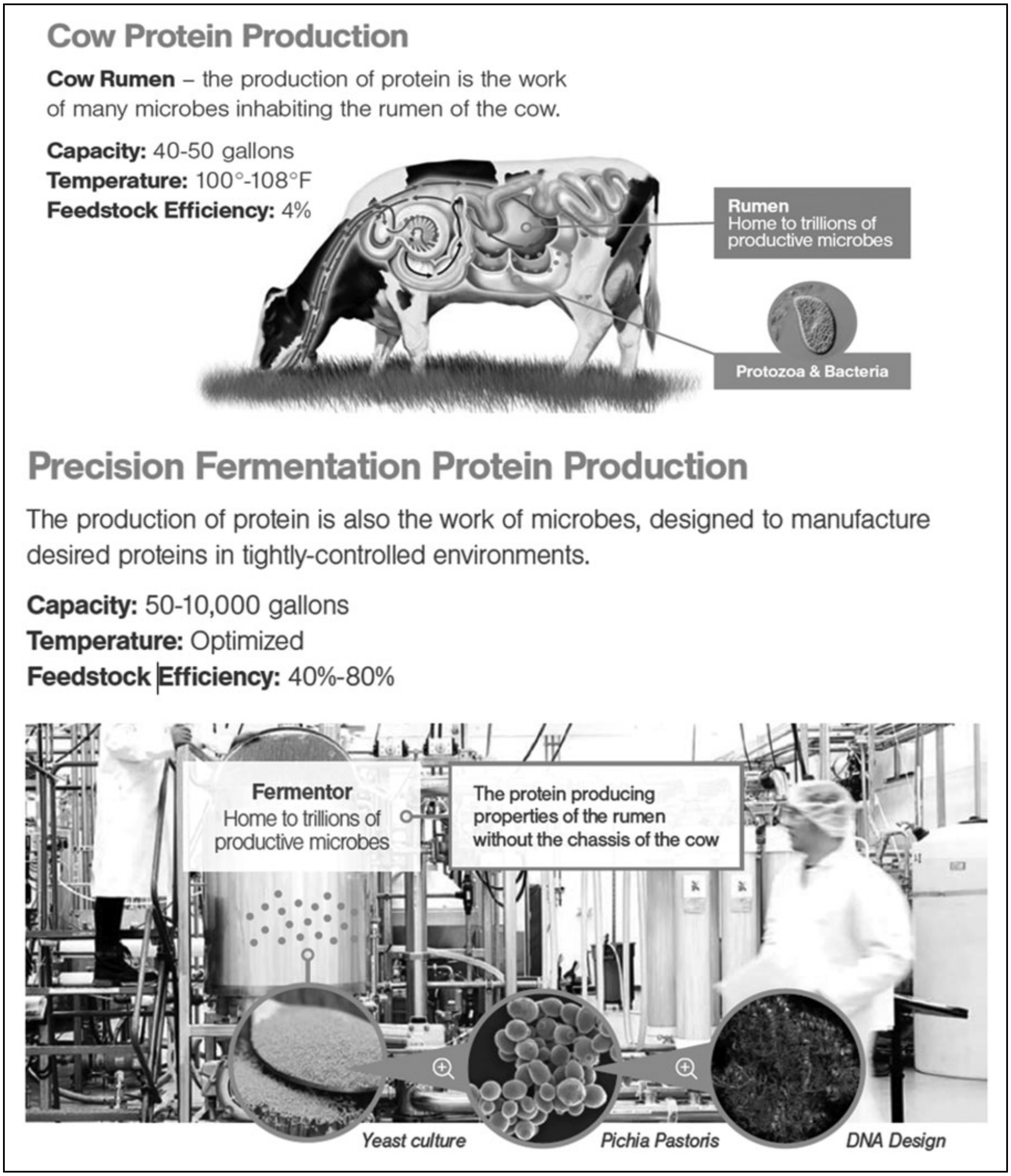

Fig 1. Precision fermentation: Protein production unplugged.

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 $1 billion in 2000 and took 13 years.[7] Today, it takes just a few days and costs about $1,000 – with a $100 genome within reach (*Fig. 2*).[8-12] The cost of computing was $50 million per teraflop in 2000. Today, a GPU for machine learning costs less than $60 per teraflop.[13]

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,

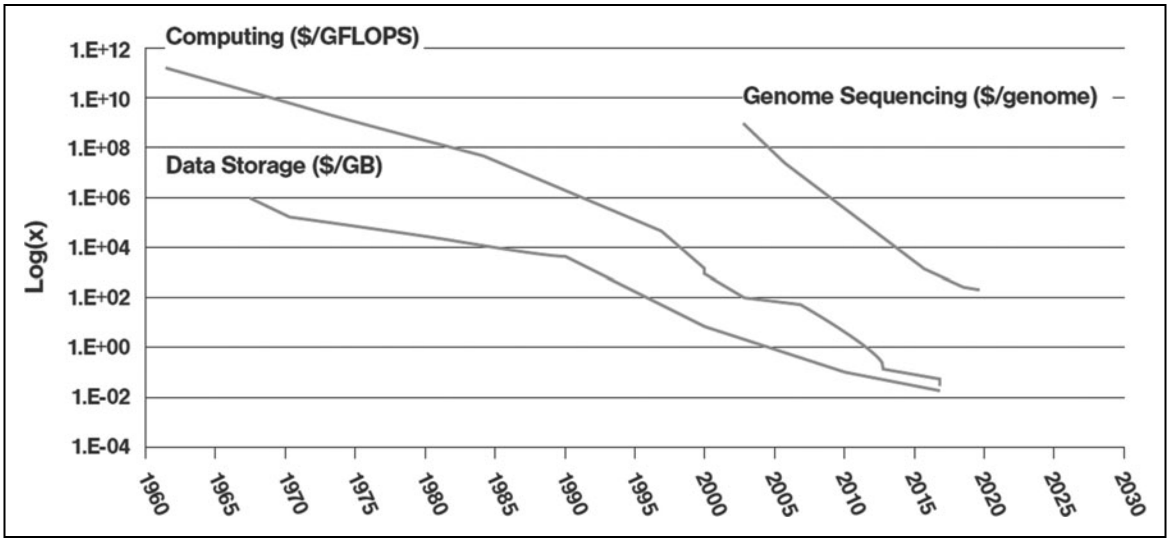

Fig 2. Costs of key underlying technologies falling exponentially.

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.

PRECISION FERMENTATION

One key process enabled by the convergence of these technologies and their rapidly falling costs is 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 microorganisms 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 microorganisms for producing human insulin[17] 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 $100 billion 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 $1 million/kg in 2000 to about $100/kg today. We expect the cost to fall below $10/kg by 2025.

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 (*Fig. 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.[23] 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

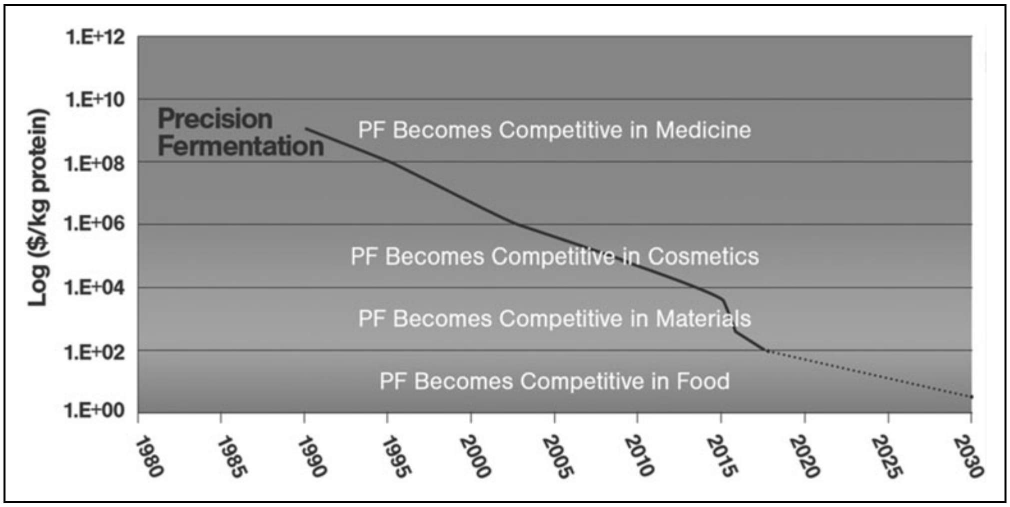

Fig 3. PF disrupting more industries as costs fall.

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.

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. 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.

Disruption and Adoption

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

THE DISRUPTION OF THE COW

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. More recently, the process is being used to make soy leghemoglobin (heme).[24] 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 microorganisms 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.

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 (substitute ingredients and substitute end products) and the way we eat (fortification and form factor.

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).

Some of these B2B ingredient disruptions can happen very quickly. 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,[25] 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 US used HFCS-55 instead of sugar.[26] This direct substitution is a B2B disruption, which means that consumer preference is not the primary driver of adoption.

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-precision-fermentation 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.[27] 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.[28]

The milk industry provides an excellent example of how this mixed ingredient disruption will play out. The milk industry is currently on a knife-edge—it operates on extremely thin margins[29] and suffers from volatile commodity prices,[30] and so relies on government subsidies[31] and support from powerful lobbying arms to stay afloat.[32] 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.[33]

The key to understanding the disruption of milk is that PFonly needs to disrupt 3.3% of the milk bottle—the key functional proteins—to bring about the collapse of the whole cow milk industry. Roughly 65% of milk proteins are consumed directly, either as drinking milk or in dairy products like cheese, yogurt, and ice cream.[34] 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.

Whey and casein proteins have become universally available and are widely-traded commodities.[35,36] Both are already being targeted for production through PF.[37] 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.[38]

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.[39] 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.[40]

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.[41] 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.[42] 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. This will add a whey glut to the bulging cheese glut in the US 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 US despite a large price premium and a different taste profile.[43]

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 US dairy protein demand to come from PF alternatives (*Fig. 4*).

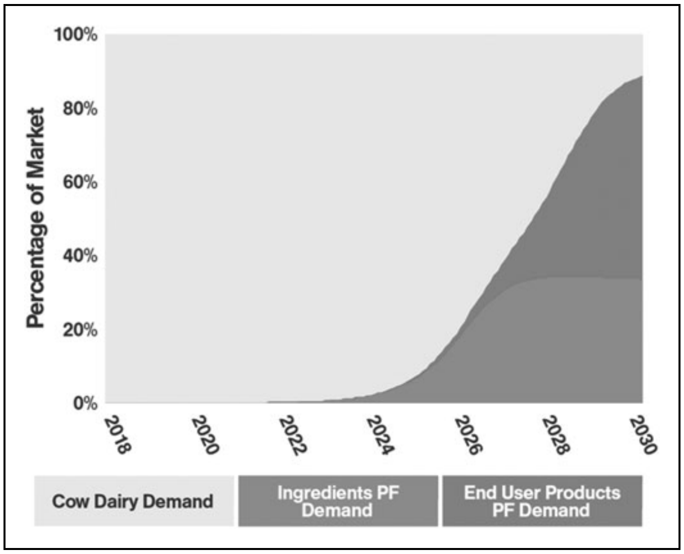

Fig 4. US dairy protein demand.

SUBSTITUTE END PRODUCTS: CELL-BASED MEATS

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 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.

Ground meat is the most significant and ubiquitous beef product, representing 40-60% of the output of a cow by volume.[44] 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[45] have been around for centuries, with more recent products like the mycoprotein-based Quorn[46] 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.[47] 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.

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 US.

The drop in the cost of ground beef and the rising cost of steak 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 US. 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.

By 2030, therefore, we expect 70% of all beef consumed to come from modern production methods (*Fig. 5*). 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.

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.[48] 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 US in 2017 was Halo Top, a startup company that launched an ice cream with more than twice as much protein as regular ice cream.[49,50] A pint of vanilla Halo Top has 280 calories, 8 grams of fat, 12 grams of fiber, and 20 grams of protein.[51] Halo Top now turns over more than $350 million 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 US 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

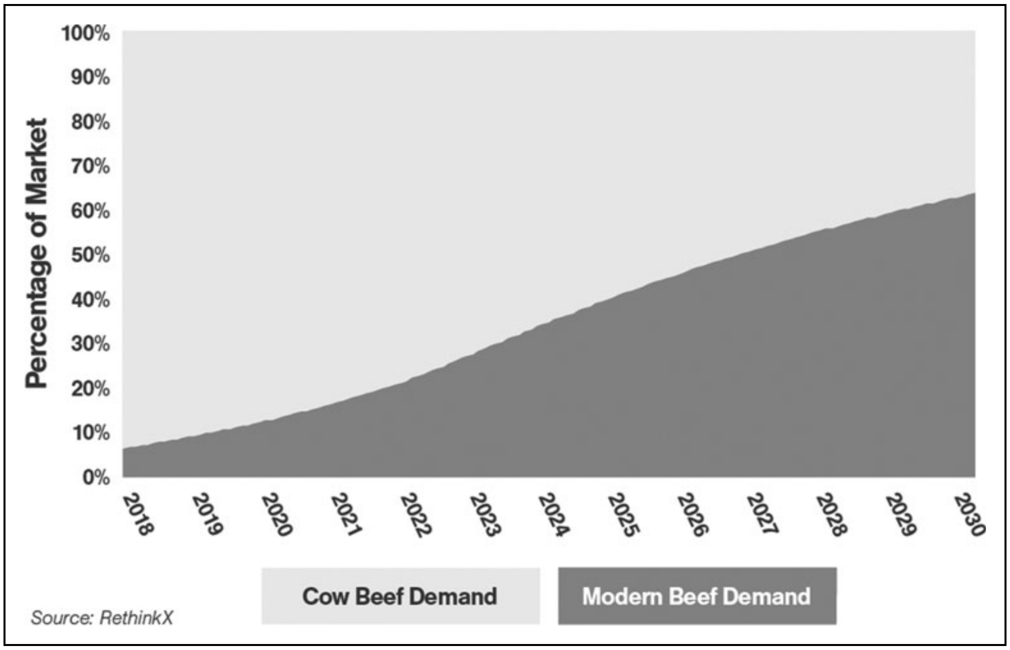

Fig 5. US market share of cow versus modern beef products.

intolerant.[52] In these markets, the lower cost of modern alternatives will drive a faster adoption as there is less attachment to conventional forms of protein.

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%.[53] 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 US.[54] 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 $2.1 billion by 2012.[55,56] 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 $4.7 billion market by 2015.[57]

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.[58] 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.

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

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. 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[59]—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. 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.

Impacts and Implications

Every aspect of the value chain will be impacted to such a degree that, by 2030, the cattle industry in the US 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 US GDP, 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 US 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 US, cows generate 13 times more bodily waste than the entire American human population.[60]

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 US cattle industry alone—while the average American family spends $1,500 of its total annual income on animal products.[61,62]

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.

IMPACTS ON THE CURRENT SUPPLY CHAIN

In our forecast, the number of cattle will drop by 50% by 2030, with revenues directly associated with cattle production falling from $95 billion to $50 billion at current prices. By 2035, we anticipate that cattle production will drop by 75% from current levels, with revenues shrinking to $20 billion. At current prices, revenues of the US beef and dairy industries and their suppliers, which together exceed $400 billion 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.

Crop farming is closely entwined with animal agriculture, with just under half of US cropland dedicated to feeding animals, both domestically and abroad.[63] While there are many varieties of crops used for livestock feed, the major staples for cattle are corn, soy, and hay. Together, US beef and dairy cattle consume about 50% of the crops produced for US livestock—70% of the hay, 45% of the corn, and 17% of the soy.[64]

As a result, crops needed to feed cattle in the US will fall by 50%, from 155 million tons in 2018 to 80 million tons in 2030.[65] 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 $60 billion in 2018 to less than $30 billion 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.[66]

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 microorganisms. 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.[67] 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,[68] 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 $1.5 billion, fertilizer revenues to $1.5 billion, and seed revenues to $750 million. Meanwhile, revenues for animal health will also be cut by more than half from current levels of almost $4 billion ($1.2 billion is spent on antibiotics and other pharmaceuticals and $2.8 billion on other veterinary services).

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 opensource 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,[69] but we also see moves for an open-source system—crowd-sourced synthetic biology (bio-hacking), for example, is becoming more and more popular.[70]

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

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.

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 US 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.[71] 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.[72] As a result, by 2030, cattle pasture, rangeland, and feed cropland will decline by about 50%. This means the disruption of the US 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.[73]

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.[74]

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.[75] 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,[76] 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 US, at least 12% can be attributed to livestock.[77]

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.[78,79]

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.[80] US agriculture as a whole is responsible for about 2% of oil products consumption, which is equivalent to about 150 million BOE per year.[81]

Wider Environmental, Social, and Economic Implications

ENVIRONMENTAL IMPLICATIONS

- Direct US greenhouse gas 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 US beef and dairy production and their associated industries will be lost by 2030, climbing towards 90% by 2035.
- Employment and incomes in all other US livestock and commercial fisheries industries will follow suit, for a total loss of more than 1.7 million jobs by 2035.
- The emerging US 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 US family will save more than $1,200 a year in food costs. This will keep an additional $100 billion 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 US, 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.

About RethinkX

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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Editor's Note

The text presented here is excerpted from a comprehensive report prepared by RethinkX, an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. The information and views expressed here are those of RethinkX and not Industrial Biotechnology or Mary Ann Liebert, Inc., publishers, or their affiliates.

Tony Seba is cofounder of RethinkX. E-mail: food@rethinkx.com. Catherine Tubb is formerly Senior Research Analyst at RethinkX. The above report is an excerpt; the entire report, including extensive detail surrounding policy recommendations and several case studies, can be found at https://www.rethinkx.com/food-and-agriculture.

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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

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29. 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. Available at: https://www.farmcrediteast.com/knowledge-exchange/Reports/2018-northeast-dairy-farm-summary, USDA, National Agricultural Statistics Service (NASS). (2019). Milk Production. Available at: https://usda.library.cornell.edu/concern/publications/h989r321c?locale=en

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31. 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. U.S. Federal and State Subsidies to Agriculture: Prepared for Dairy Farmers of Canada (2018). Available at: http://greyclark.com/wp-content/uploads/2018/02/US-Subsidies-Post-2014-Farm-Bill-FEB-2018.pdf. Wallin S. Checkoff's Pizza Hut Partnership Leads To 25% More Cheese On Pan Pizzas (2019). Dairy Management Inc. Available at: https://dairy.org/news/checkoffs-pizza-hut-partnership-leads-to-25-more-cheese-on-pan-pizzas USDA, NASS. (2019). Cold Storage. Available at: https://usda.library.cornell.edu/concern/publications/pg15bd892?locale=en

32. 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. Available at: https://opensecrets.org/industries/lobbying.php?ind=A04++

33. Milk Facts. Milk Composition. Available at: http://milkfacts.info/Milk%20Composition/Milk%20Composition%20Page.htm

34. RethinkX estimates based on company and industry data

35. 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. Available at: https://globalfoodforums.com/wp-content/uploads/2016/05/3-Dairy-Protein-Markets-Banderob.pdf; UN Comtrade. 350220 Milk Albumin [Data File]. Trade Map. Available at: https://trademap.org/Country_SelProduct_TS.aspx?nvpm=1%7c%7c%7c%7c%7c350220%7c%7c%7c6%7c1%7c1%7c2%7c2%7c1%7c2%7c3%7c1 UN Comtrade. 3501105000 Other Casein, Except Of Milk Protein Concentrate [Data File]. Trade Map. Available at: https://trademap.org/Country_SelProduct_TS.aspx?nvpm=1%7c%7c%7c%7c%7c%7cTOTAL%7c%7c%7c2%7c1%7c1%7c2%7c2%7c1%7c2%7c1%7c%7c1

36. 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]. Available at: https://ers.usda.gov/data-products/food-availability-per-capita-data-system/ The data serve as proxies for actual consumption at the national level.

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

38. Sugar Prices 37 Year Historical Chart [Data File]. Macrotrends. Available at: https://macrotrends.net/2537/sugar-prices-historical-chart-data

39. 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 a creamier froth.

40. This is a massively subsidized industry. If animal agriculture were a free market, the disappearance of a third of revenues would be enough to push it into bankruptcy.

41. Umhoefer J. The whey problem and California's Solution. *Cheese Market News*. Available at: https://cheesemarketnews.com/guestcolumn/2015/08may15_02.html

42. Danovich T. One pound of cheese makes nine pounds of whey. Where does it all go (2018)? The New Food Economy. Available at: https://thecounter.org/whey-disposal-reuse-cheese-dairy-byproduct/

43. Bushnell C. Newly Released Market Data Shows Soaring Demand for Plant Based Food (2018). Good Food Institute (GFI). Available at: https://gfi.org/blog/newly-released-market-data-shows-soaring/

44. Close D. Ground Beef Nation: The Effect of Changing Consumer Tastes and Preferences on the U.S. Cattle Industry (2014). Rabobank. Available at: https://beefcentral.com/wp-content/uploads/2014/06/Ground-Beef-Nation.pdf

45. Seitan is another name for wheat gluten. Tofu is made from soybeans.

46. Quorn is a mycoprotein-based product which was launched commercially in 1985. Available at: https://quorn.us/

47. Beyond Meat and Impossible Foods are amongst the most high-profile.

48. American Egg Board. Yes, It Really Is Incredible - The Indisputably Potent Protein Eggs Supply. Available at: https://aeb.org/search/result-item/98-cwhite-papers/584-protein

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50. Watson E. IRI pacesetters: What were the top 10 new food launches in 2017 (2018). *Food Navigator.* Available at: https://foodnavigator-usa.com/Article/2018/04/16/IRI-pacesetters-What-were-the-top-10-new-food-and-beverage-product-launches-in-2017

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54. Altitrade Partners. This Could Be A Huge Game-Changer For The Energy Drink Market (2015). Available at: https://seekingalpha.com/article/3105846-this-could-be-a-huge-game-changer-for-the-energy-drink-market

55. Coleman ML. Hard to Swallow: How the military, a marathoner, and the relentless march of capitalism turned protein bars into an unlikely American staple (2019). Topic, 20. Available at: https://topic.com/hard-to-swallow

56. Agriculture and Agri-Food Canada. International Markets Bureau. Snack, Cereal and Nutrition Bars in the United States. Available at: http://publications.gc.ca/site/eng/9.803238/publication.html

57. Daniells S. Protein Powders: The Heavyweight in the $16bn Sports Nutrition Market (2015). *Food Navigator.* Available at: https://foodnavigator-usa.com/Article/2015/09/17/Protein-powders-The-heavyweight-in-the-16bn-sports-nutrition-market

58. Bistro In Vitro is a fictitious restaurant with a creative menu based on cellular agriculture and the possibilities it enables, imagined by a group of artists, designers, chefs, scientists, and philosophers. Available at: https://bistro-invitro.com/en/starters/

59. This point is an estimate based on our analysis of the industry margins and operating and financial leverage.

60. What Happens to Animal Waste. FoodPrint. Available at: https://foodprint.org/issues/what-happens-to-animal-waste/#easy-footnote-bottom-1-1324

61. In this instance, the cattle industry includes cattle ranching and farming, animal food production, dairy product production, animal slaughtering and processing, and leather and hide tanning and finishing. RethinkX estimate. Source: Bureau of Labor Statistics. Available at: https://bls.gov/home.htm; Almost two million people are employed in animal agriculture in the U.S.

62. BLS. Consumer Expenditure Survey. Consumers spend, on average, 2% of their expenditures on meat, dairy, eggs, fish and poultry (2017). Available at: https://bls.gov/cex/tables.htm#avgexp

63. This includes 38% of the corn crop, 35% of the soybean crop, and 95% of hay production. RethinkX estimate. Merrill D, Leatherby, L. Here's How America Uses Its Land (2018). Bloomberg. Available at: https://bloomberg.com/graphics/2018-us-land-use/

64. Crop consumption does vary considerably by species—corn goes mostly to cattle (45%) while soy goes mostly to feeding chickens (58%) and pigs (23%). Exports of feed crops, which account for 15% of total cropland, will also be affected by the disruption. In 2017, 50% of soybean (57% of exports go to China for pig feed) and 15% of corn production was exported. RethinkX estimate, USDA, National Corn Growers Association, United Soybean Board, UN Comtrade.

65. 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. Available at: https://nass.usda.gov/Publications/Ag_Statistics/2017/Complete%20Ag%20Stats%202017.pdf

66. While cows typically have a feed conversion: edible product ratio (ratio of input to output) of around 25:1, modern foods will have a ratio closer to 2:1. This means that to produce the same amount of beef, it will take 10 to 25 times less feed. Different producers are using different crops for this purpose at the moment, but in the future it will be possible to use almost any biomatter, including bio waste products or products not digestible by humans (such as leaves) to feed cells.

67. MacDonald JM, Hoppe RA. Large Family Farms Continue To Dominate U.S. Agricultural Production (2017). USDA, ERS. Available at: https://ers.usda.gov/amber-waves/2017/march/large-family-farms-continue-to-dominate-us-agricultural-production/

68. American farmers have continuously adopted technology and adapted to market conditions to improve profitability. For example, the number of acres planted with GMO soy crops grew from around 17% of acres in 1997 to 68% in 2001, before plateauing at 94% in 2014. USDA, ERS. (2018, July 16). Recent Trends in GE Adoption. Available at: https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx

69. Merck's Innovation Center invests in forward-looking ideas, identifying Innovation Fields where they see potential for new business. One of these is clean meat. Available at: https://emdgroup.com/en/research/innovation-center/innovation-fields.html

70. Integriculture (Japan) is a venture-funded cell-based meat startup company and Shojinmeat Project (Japan) is a citizen science community working toward open-source, cell-based meat production.

71. This estimate includes feed exports as part of feed crop acreage.

72. Khan S, Loyola C, Dettling, J, et al. Comparative environmental LCA of the Impossible Burger with conventional ground beef burger (2019). Quantis for Impossible Foods. Available at: https://impossiblefoods.com/if-pr/LCA-Update-2019/

73. The Louisiana purchase (1803) between France and the U.S. doubled the size of the country and expanded its territory from the Mississippi River to the Rocky Mountains, and from the Gulf of Mexico to the Canadian border. Louisiana Purchase. (2019). History. Available at: https://history.com/topics/westward-expansion/louisiana-purchase

74. We use the term reforestation to encompass both reforestation and afforestation - growing trees to establish forest cover on grounds that have either been cleared of forest in the recent past, distant past or have never had forest cover.

75. The production of synthetic fabrics such as polyester, nylon and acrylic opened up the clothing market and has allowed for inexpensive mass production of fabric for clothing and other uses. These plastic-containing materials are of the largest source (35%) of microplastics in the ocean (and in landfills), a major, far reaching, global pollution problem. BoucherJ, Friot D. Primary Microplastics in the Oceans: A Global Evaluation of Sources (2017). International Union for Conservation of Nature (IUCN). Available at: https://doi.org/10.2305/IUCN.CH.2017.01.en

76. Cattle are typically moved 6 times between farms, travelling around 200 miles on a livestock truck, before they are slaughtered. Kannan N, Saleh A, Osei. Estimation of energy consumption and greenhouse gas emissions of transportation in beef cattle production. *Energies* 2016;9(11),960. Available at: https://doi.org/10.3390/en9110960

77. This estimate includes live animals & fish, animal feed, meat & seafood, cereal grains (40%), fertilizers (40%), milk, and milk fat (2017). Center for Transportation Analysis. Freight Analysis Framework Data Tabulation Tool [Data File].

78. Refrigerators in food storage, retail, and transportation are large consumers of energy throughout the supply chain. Refrigeration is responsible for about 40% of energy use in grocery stores and supermarkets and about 14% of household energy.

79. A report from the UK suggests that about 6% of total energy is used for non-household refrigeration, including retail display, refrigerated transport, and cold storage. Meat and dairy chilling are large contributors to this total, so we can assume that any reduction in these could have a noticeable impact on energy use in the U.S. as well. Currently, there are approximately 635 million kgs of cheese and 1.2 billion kgs of meat in U.S. cold storage, which implies significant energy use. RethinkX estimate, Swain M. Energy use in food refrigeration (2008). University of Bristol. Available at: https://grimsby.ac.uk/documents/defra/usrs-top10users.pdf

80. About 1% of U.S. oil product consumption. EIA. FAQ: How much oil is consumed in the United States (2019). Available at: https://eia.gov/tools/faqs/faq.php?id=33&t=6; Hitaj C. Energy Consumption and Production in Agriculture (2017). USDA, ERS. Available at: https://ers.usda.gov/amber-waves/2017/januaryfebruary/energy-consumption-and-production-in-agriculture/

81. Percentage applied to 2019 total. Includes consumption for agriculture and forestry. International Energy Agency (IEA). United States: Balances for 2016 [Data File]. IEA World Energy Balances 2018: Statistics data browser. Available at: https://iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource; EIA. (2019). Available at: https://eia.gov/tools/faqs/faq.php?id=33&t=6